Chapter 3

Energy, Energy Transfer, And General Energy Analysis

Objectives

- Introduce the concept of energy and define its various forms.
- Discuss the nature of internal energy.
- Define the concept of heat and the terminology associated with energy transfer by heat.
- Define the concept of work, including electrical work and several forms of mechanical work.
- Introduce the first law of thermodynamics, energy balances, and mechanisms of energy transfer to or from a system.

Objectives

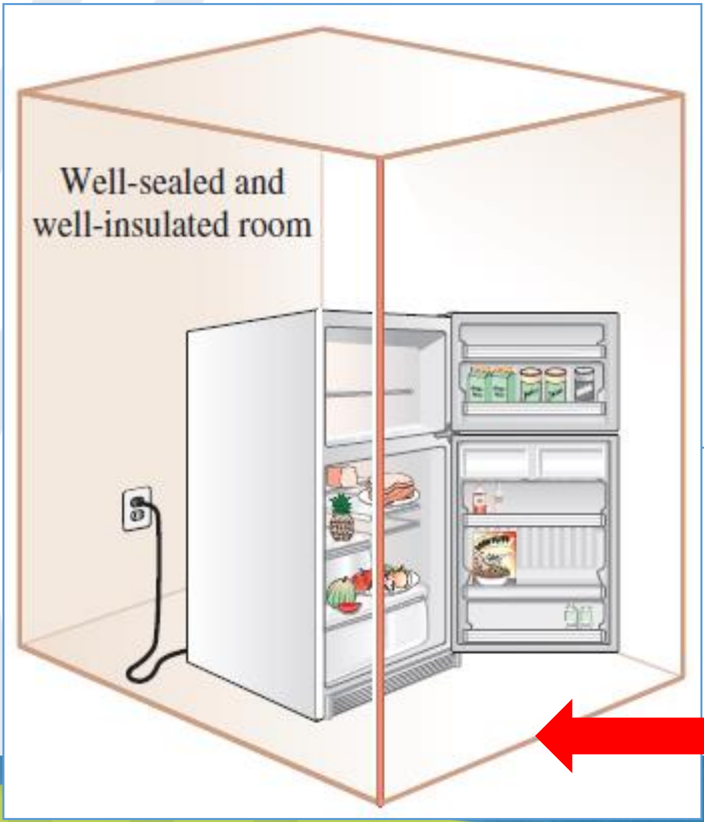
- **Determine that a fluid flowing across a control surface of a control volume carries energy across the control surface in addition to any energy transfer across the control surface that may be in the form of heat and/or work.**

- **Define energy conversion efficiencies.**

3-1 INTRODUCTION

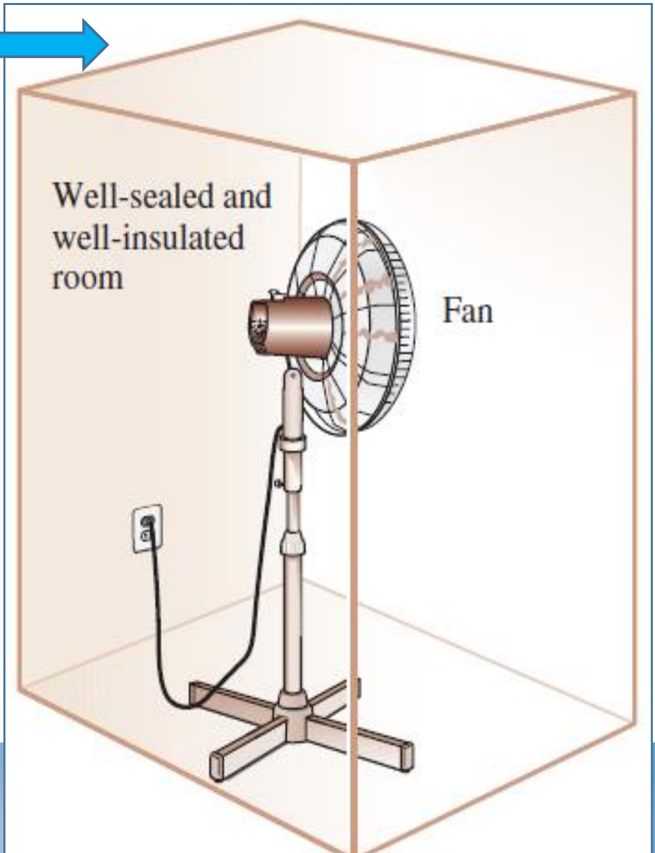
If we take the entire room—including the air and the refrigerator (or fan)—as the system, which is an adiabatic closed system since the room is well-sealed and well-insulated, the only energy interaction involved is the electrical energy crossing the system boundary and entering the room.

As a result of the conversion of electric energy consumed by the device to heat, the room temperature will rise.



A fan running in a well-sealed and well-insulated room will raise the temperature of air in the room.

A refrigerator operating with its door open in a well-sealed and well-insulated room



3-2 FORMS OF ENERGY

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **total energy, *E*** of a system.
- Thermodynamics deals only with the ***change*** of the total energy.
- **Macroscopic forms of energy**: Those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies.
- **Microscopic forms of energy**: Those related to the molecular structure of a system and the degree of the molecular activity.
- **Internal energy, *U***: The sum of all the microscopic forms of energy.

3-2 FORMS OF ENERGY

- **Kinetic energy, KE:** The energy that a system possesses as a result of its motion relative to some reference frame.

- **Potential energy, PE:** The energy that a system possesses as a result of its elevation in a gravitational field

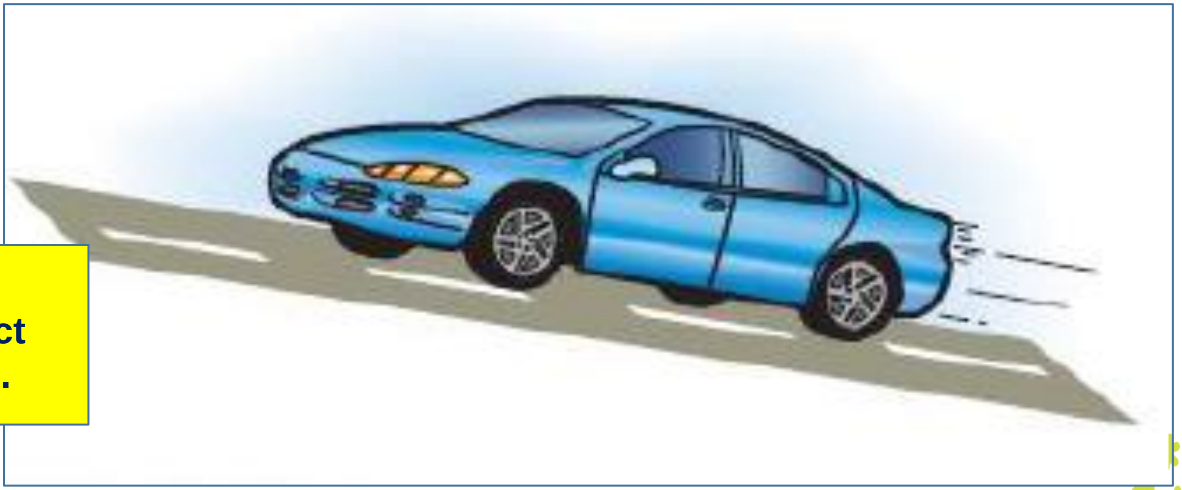
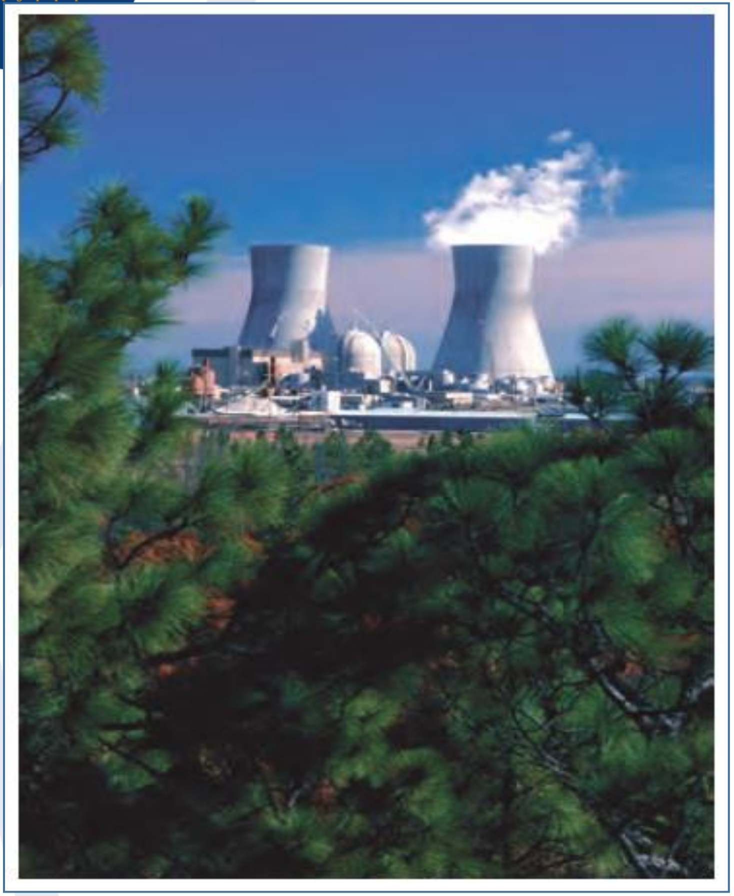


FIGURE 3-4
The macroscopic energy of an object changes with velocity and elevation.

3-2 FORMS OF ENERGY-1



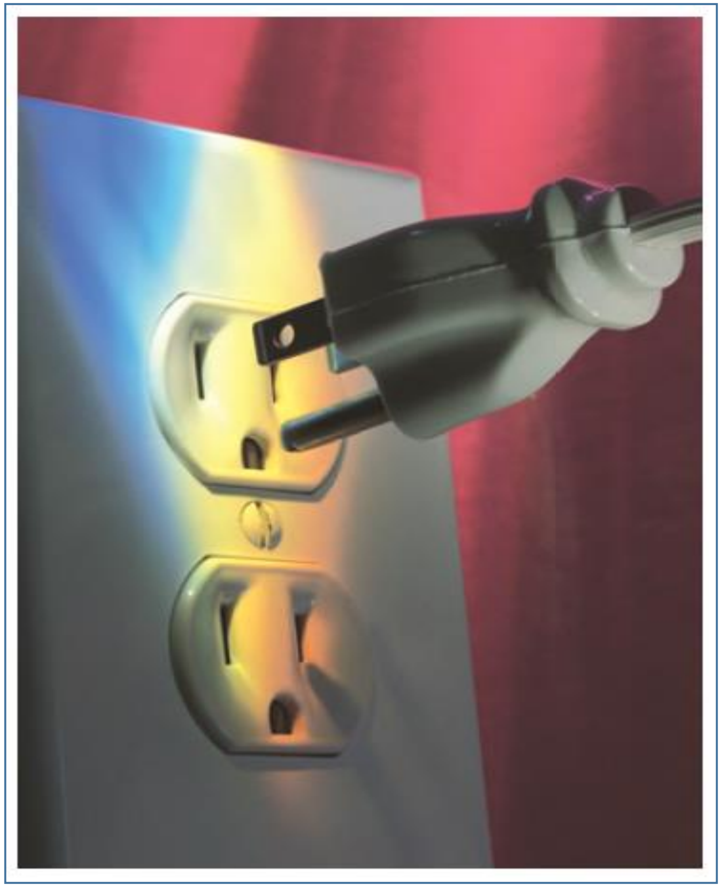


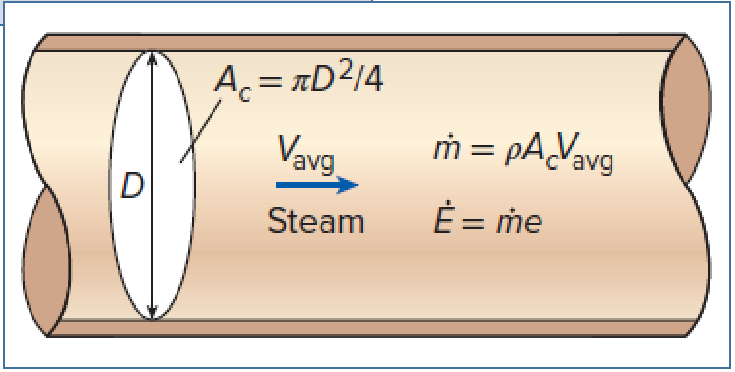
FIGURE 3-3

At least six different forms of energy are encountered in bringing power from a nuclear plant to your home: nuclear, thermal, mechanical, kinetic, magnetic, and electrical.

3-2 FORMS OF ENERGY-2

$$\mathbf{KE} = m\frac{V^2}{2} \quad \text{(kJ)}$$ Kinetic energy

$$\text{ke} = \frac{V^2}{2} \quad \text{(kJ/kg)}$$ **Kinetic energy per unit mass**



Mass flow rate

$$\dot{m} = \rho\dot{V} = \rho A_c V_{avg} \quad \text{(kg/s)}$$

Potential energy

$$\text{PE} = mgz \quad \text{(kJ)}$$

Potential energy per unit mass

$$\text{pe} = gz \quad \text{(kJ/kg)}$$

Energy flow rate

$$\dot{E} = \dot{m}\mathbf{e} \quad \text{(kJ/s or kW)}$$

$$E = U + \text{KE} + \text{PE} = U + m\frac{V^2}{2} + mgz \quad \text{(kJ)}$$ **Total energy of a system**

$$e = u + \text{ke} + \text{pe} = u + \frac{V^2}{2} + gz \quad \text{(kJ/kg)}$$ **Energy of a system per unit mass**

Total energy per unit mass

$$\mathbf{e} = \frac{E}{m} \quad \text{(kJ/kg)}$$

Some Physical Insight to Internal Energy

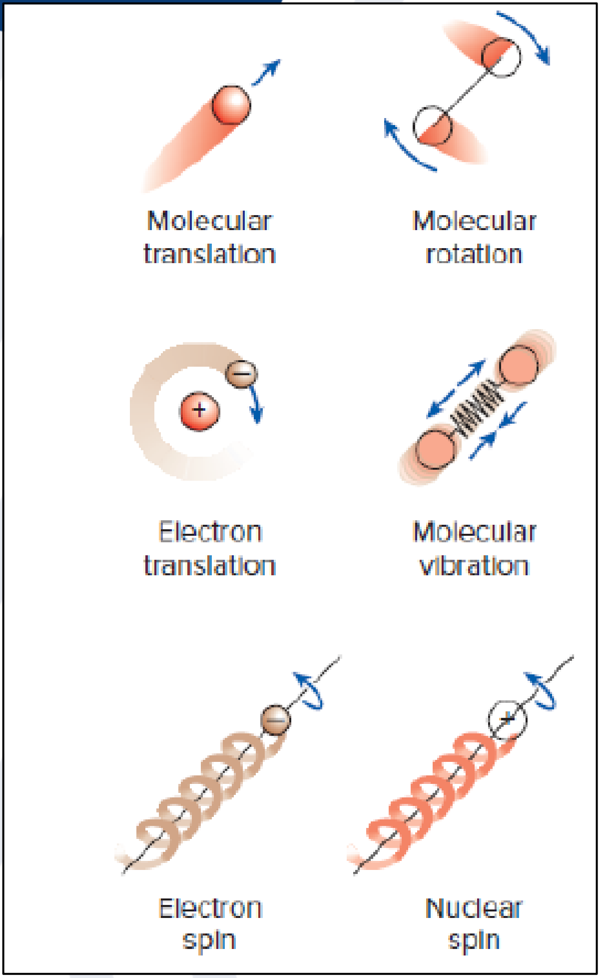


FIGURE 3-6
The various forms of microscopic energies that make up *sensible* energy.

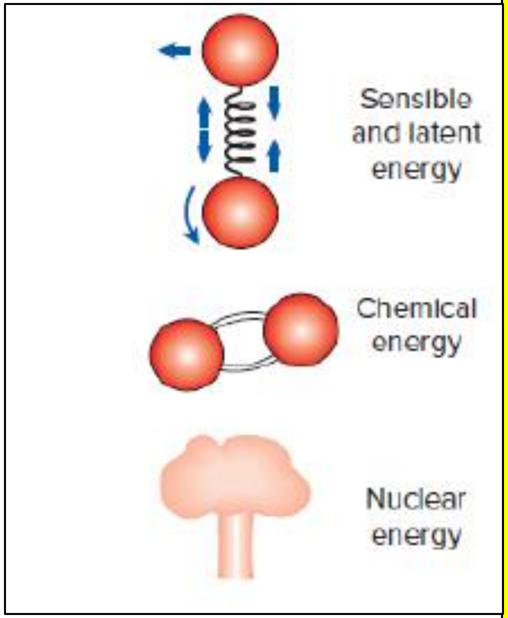


FIGURE 3-7
The internal energy of a system is the sum of all forms of the microscopic energies.

Sensible energy: The portion of the internal energy of a system associated with the kinetic energies of the molecules.

Latent energy: The internal energy associated with the phase of a system.

Chemical energy: The internal energy associated with the atomic bonds in a molecule.

Nuclear energy: The tremendous amount of energy associated with the strong bonds within the nucleus of the atom itself.

Thermal = Sensible + Latent

Internal = Sensible + Latent + Chemical + Nuclear

Some Physical Insight to Internal Energy-1

- The total energy of a system, can be *contained* or *stored* in a system, and thus can be viewed as the ***static* forms of energy.**
- The forms of energy not stored in a system can be viewed as the ***dynamic* forms of energy** or as ***energy interactions*.**
- The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process.
- The only two forms of energy interactions associated with a closed system are **heat transfer** and **work.**

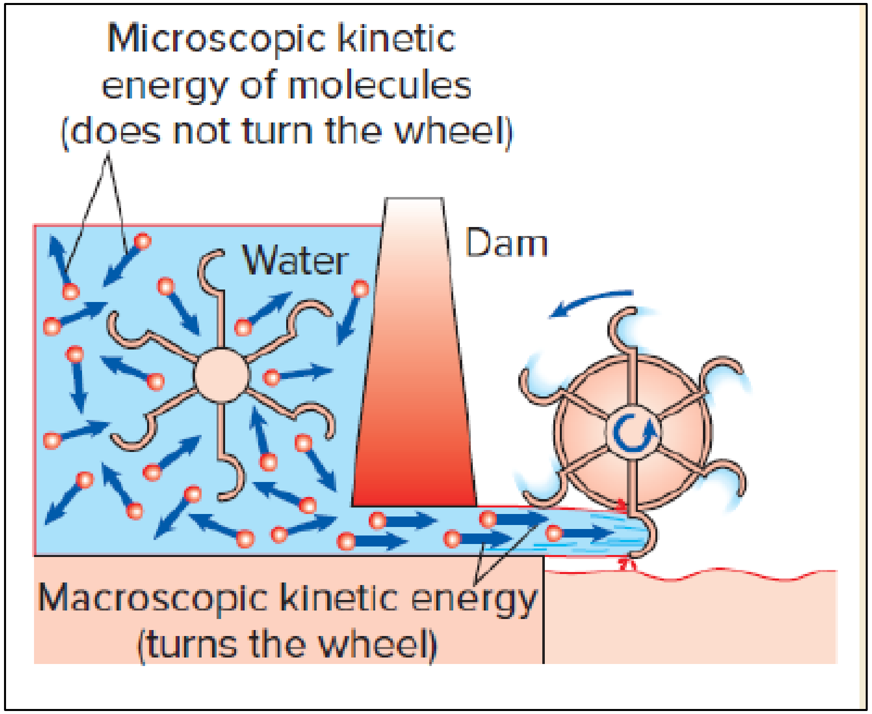


FIGURE 3-8
The *macroscopic* kinetic energy is an organized form of energy and is much more useful than the disorganized *microscopic* kinetic energies of the molecules.

- **The difference between heat transfer and work:** An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise, it is work.

More on Nuclear Energy

- Nuclear energy by **fusion** is released when two small nuclei combine into a larger one.
- The uncontrolled fusion reaction was achieved in the early 1950s, but all the efforts since then to achieve controlled fusion by massive lasers, powerful magnetic fields, and electric currents to generate power have failed.

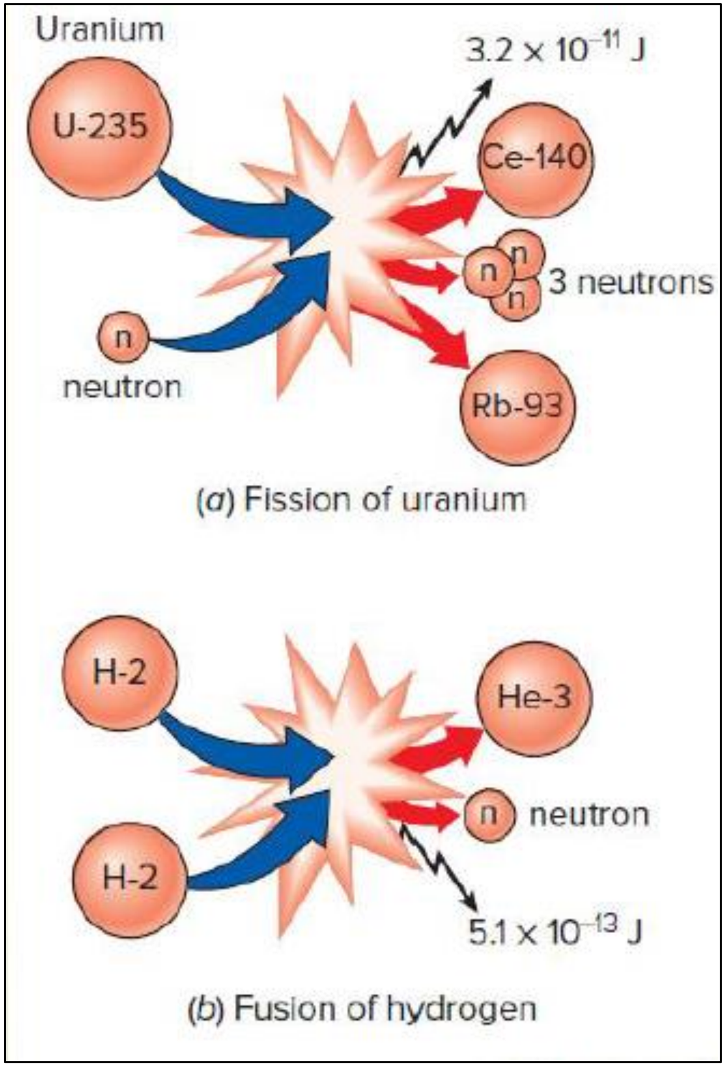


FIGURE 3-9
The fission of uranium and the fusion of hydrogen during nuclear reactions, and the release of nuclear energy.

More on Nuclear Energy

- The best-known fission reaction involves the split of the uranium atom (the U-235 isotope) into other elements and is commonly used to generate electricity in nuclear power plants (440 of them in 2004, generating 363,000 MW worldwide), to power nuclear submarines and aircraft carriers, and even to power spacecraft as well as building nuclear bombs.

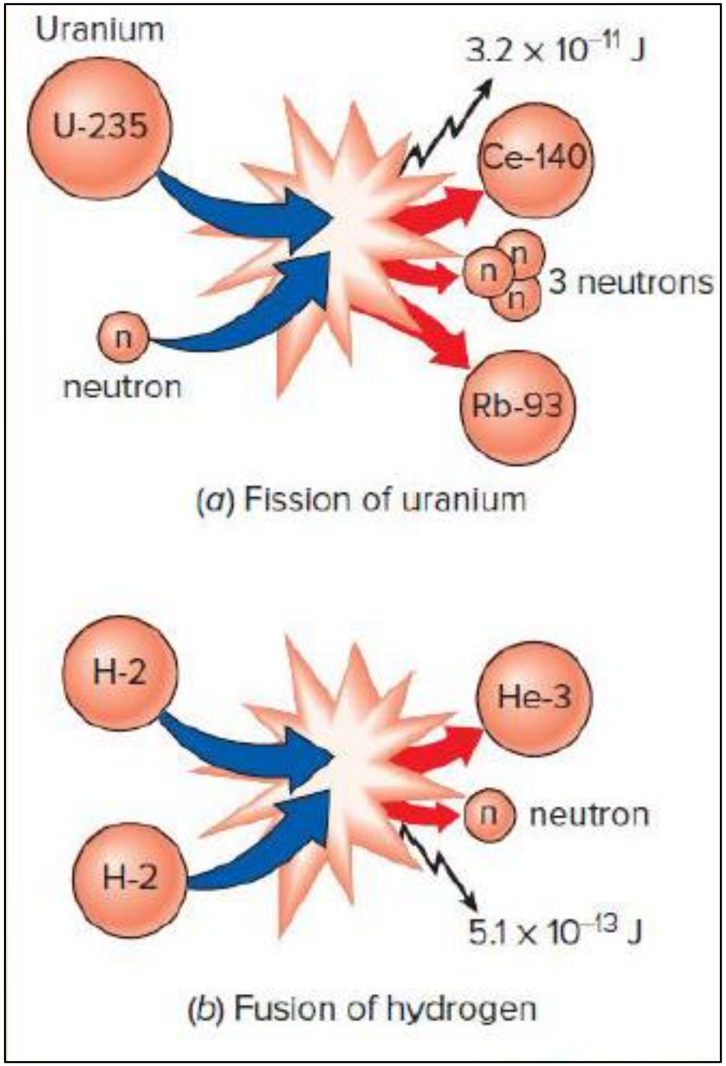


FIGURE 3-9
The fission of uranium and the fusion of hydrogen during nuclear reactions, and the release of nuclear energy.

Mechanical Energy

Mechanical energy: The form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine.
Kinetic and potential energies: The familiar forms of mechanical energy.

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

Mechanical energy of a flowing fluid per unit mass

$$\dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

Rate of mechanical energy of a flowing fluid

Mechanical energy change of a fluid during incompressible flow per unit mass

$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \quad \text{(kJ/kg)}$$

Rate of mechanical energy change of a fluid during incompressible flow

$$\Delta\dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \quad \text{(kW)}$$

EXAMPLE 3–1 A Car Powered by Nuclear Fuel

An average car consumes about 5 L of gasoline a day, and the capacity of the fuel tank of a car is about 50 L. Therefore, a car needs to be refueled once every 10 days. Also, the density of gasoline ranges from 0.68 to 0.78 kg/L, and its lower heating value is about 44,000 kJ/kg (i.e., 44,000 kJ of heat is released when 1 kg of gasoline is completely burned). Suppose all the problems associated with the radioactivity and waste disposal of nuclear fuels are resolved, and a car is to be powered by U-235. If a new car comes equipped with 0.1-kg of the nuclear fuel U-235, determine if this car will ever need refueling under average driving conditions (**Fig. 3–10**).

FIGURE 3–10
Schematic for **Example 3–1**.

SOLUTION

A car powered by nuclear energy comes equipped with nuclear fuel. It is to be determined if this car will ever need refueling.

Assumptions

1 Gasoline is an incompressible substance with an average density of 0.75 kg/L. **2** Nuclear fuel is completely converted to thermal energy.

Analysis

The mass of gasoline used per day by the car is

$$m_{\text{gasoline}} = (\rho V)_{\text{gasoline}} = (0.75\ \text{kg/L})(5\ \text{L/day}) = 3.75\ \text{kg/day}$$

Noting that the heating value of gasoline is 44,000 kJ/kg, the energy supplied to the car per day is

$$\begin{aligned} E &= (m_{\text{gasoline}})(\text{Heating value}) \\ &= (3.75\ \text{kg/day})(44{,}000\ \text{kJ/kg}) = 165{,}000\ \text{kJ/day} \end{aligned}$$

The complete fission of 0.1 kg of uranium-235 releases

$$(6.73 \times 10^{10}\ \text{kJ/kg})(0.1\ \text{kg}) = 6.73 \times 10^{9}\ \text{kJ}$$

of heat, which is sufficient to meet the energy needs of the car for

$$\text{No. of days} = \frac{\text{Energy content of fuel}}{\text{Daily energy use}} = \frac{6.73 \times 10^{9}\ \text{kJ}}{165{,}000\ \text{kJ/day}} = \mathbf{40{,}790\ days}$$

which is equivalent to about 112 years. Considering that no car will last more than 100 years, this car will never need refueling. It appears that nuclear fuel of the size of a cherry is sufficient to power a car during its lifetime.

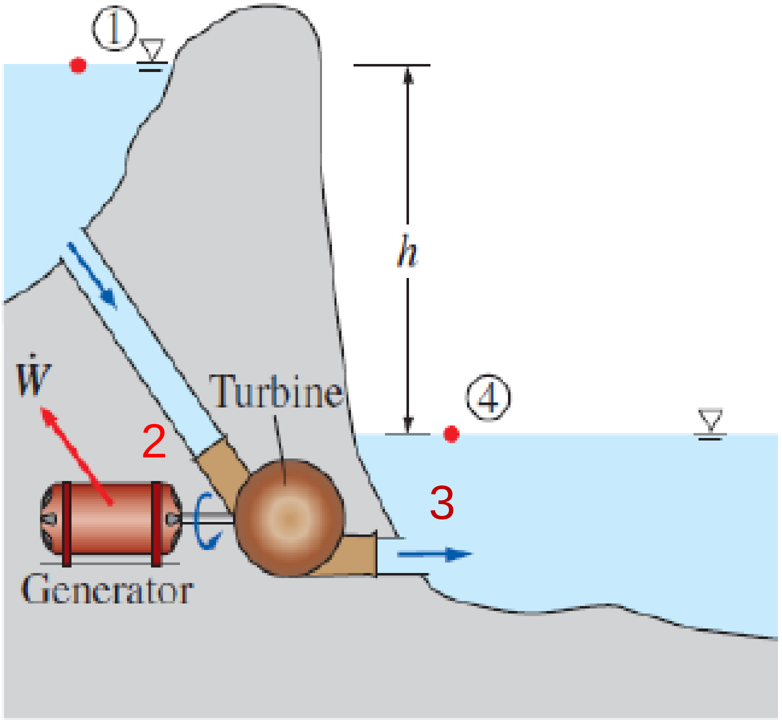
Discussion

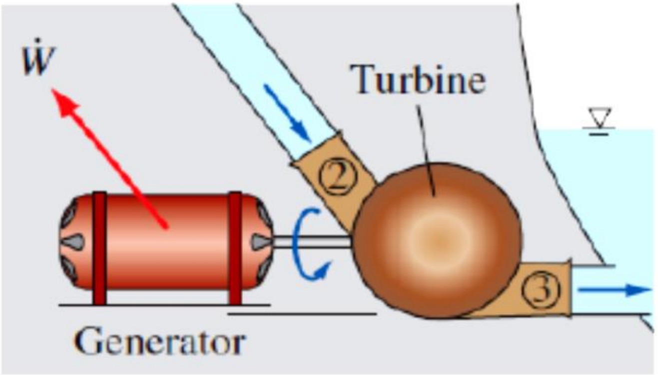
Note that this problem is not quite realistic since the necessary critical mass cannot be achieved with such a small amount of fuel. Further, all of the uranium cannot be converted in fission, again because of the critical mass problems after partial conversion.

Mechanical Energy-1

FIGURE 3-11
Mechanical energy is a useful concepts for flows that do not involve significant heat transfer or energy conversion, such as the flow of gasoline from an underground tank into a car.

Mechanical Energy-2





$$\dot{W}_{\max} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\frac{P_2 - P_1}{\rho} = \dot{m}\frac{\Delta P}{\rho}$$

since $V_2 \approx V_3$ **and** $z_2 = z_3$

(b)

FIGURE 3 -12
Mechanical Energy is illustrated by an ideal hydraulic turbine coupled with an ideal generator, In the absence of irreversible losses, the maximum produced power is proportional to *(a)* the change in water surface elevation from the up-stream to the downstream reservoir or *(b)* (close-up view) the drop-in water pressure from just upstream to just downstream of the turbine.

$$\dot{W}_{\max} = \dot{m}\Delta e_{\text{mech}} = \dot{m}g(z_1 - z_4) = \dot{m}gh$$

since $P_1 \approx P_4 = P_{\text{atm}}$ **and** $V_1 = V_4 \approx 0$

(a)

3-3 ENERGY TRANSFER BY HEAT

Heat: The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.

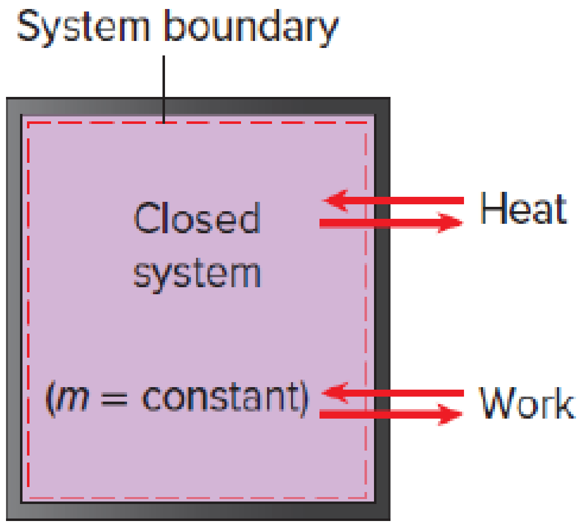


FIGURE 3-14
Energy can cross the boundaries of a closed system in the form of heat and work.

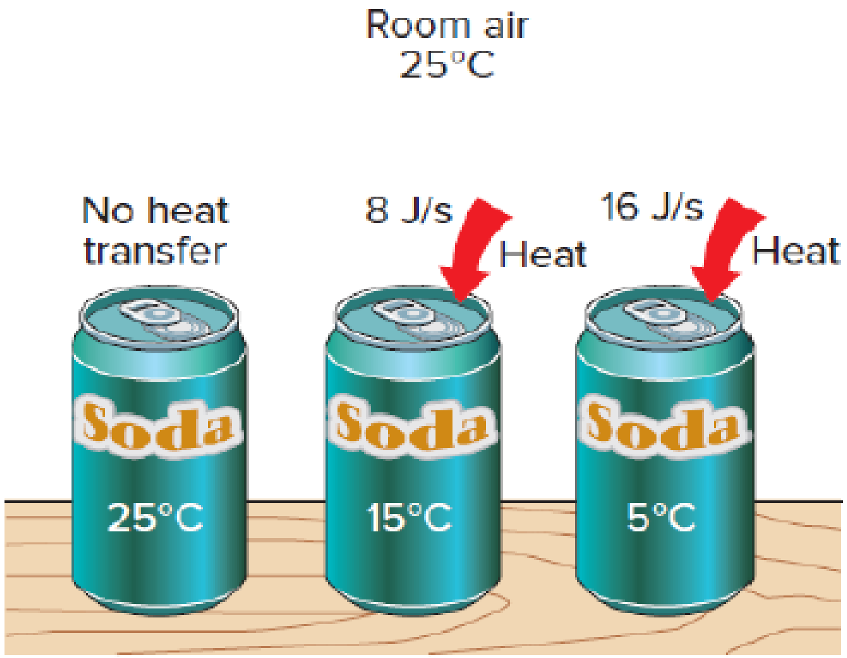


FIGURE 3-15
Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.

3-3 ENERGY TRANSFER BY HEAT-1

$$q = \frac{Q}{m} \qquad (\text{kJ/kg})$$

Heat transfer per unit mass

$$Q = \dot{Q}\,\Delta t \quad (\text{kJ})$$

Amount of heat transfer when heat transfer rate is constant

$$Q = \int_{t_1}^{t_2} \dot{Q}\,dt \qquad (\text{kJ})$$

Amount of heat transfer when heat transfer rate changes with time

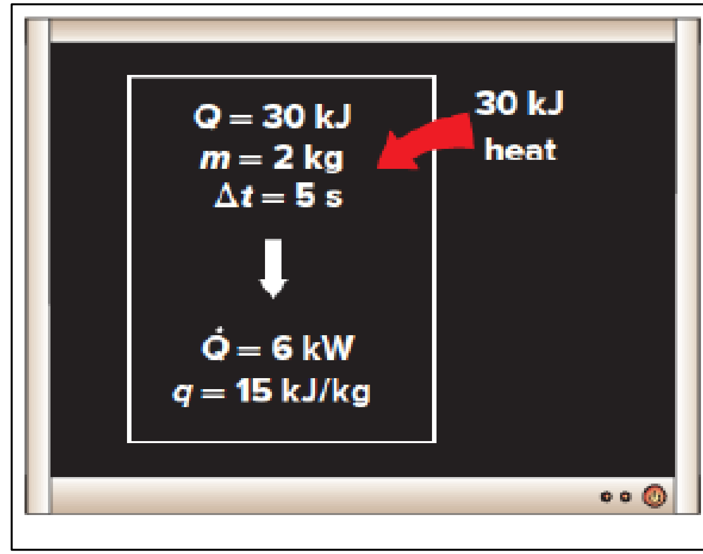


FIGURE 3-18
The relationships among q, Q, and $\dot{Q}$.

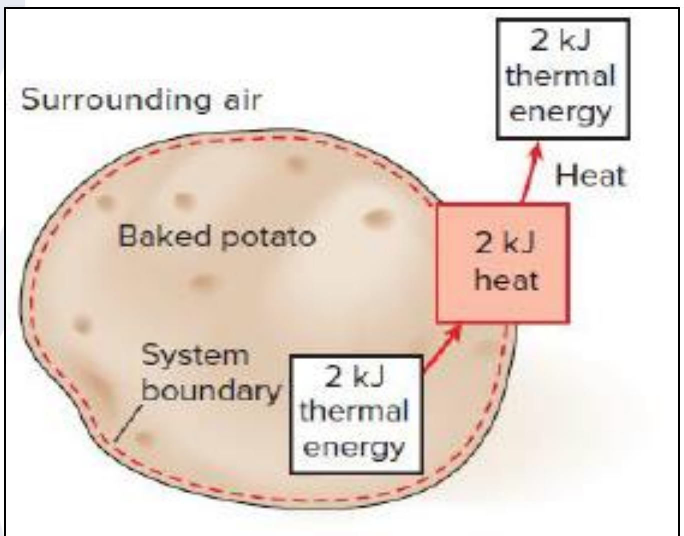


FIGURE 3-16
Energy is recognized as the heat transfer only as is crosses the system boundary.

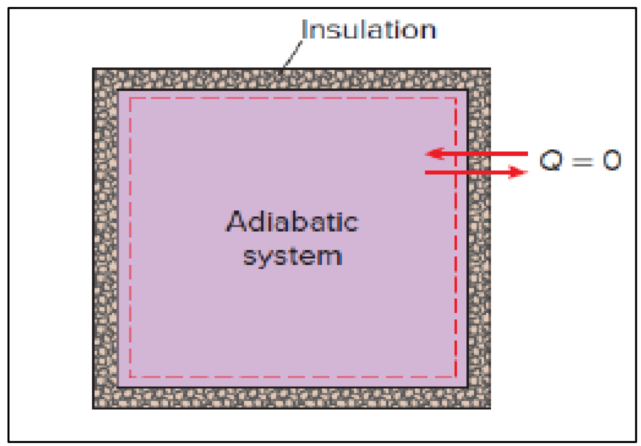


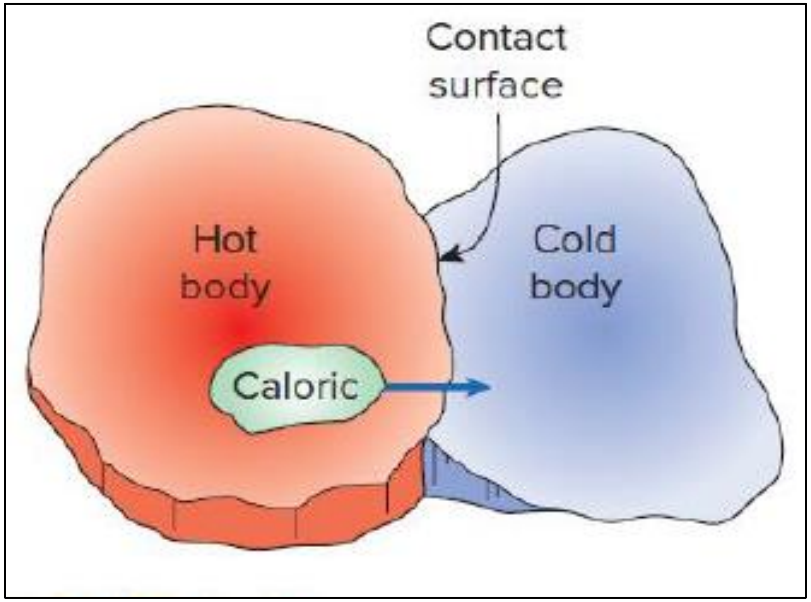
FIGURE 3-17
During an adiabatic process, a system exchanges no heat with its surroundings.

Historical Background on Heat

- **Kinetic theory:** Treats molecules as tiny balls that are in motion and thus possess kinetic energy.
- **Heat:** The energy associated with the random motion of atoms and molecules.

Heat transfer mechanisms:

- **Conduction:** The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interaction between particles.
- **Convection:** The transfer of energy between a solid surface and the adjacent fluid that is in motion, and it involves the combined effects of conduction and fluid motion.
- **Radiation:** The transfer of energy due to the emission of electromagnetic waves (or photons).



FIGUIRE 3-19
In the early nineteenth century, heat was thought to be an invisible fluid called *caloric* that flowed from warmer bodies to the cooler ones.

3-4 ENERGY TRANSFER BY WORK

- **Work:** **The energy transfer associated with a force acting through a distance.**
  - ✓ A rising piston, a rotating shaft, and an electric wire crossing the system boundaries are all associated with work interactions.
- **Formal sign convention:** ***Heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative.***
- **Alternative to sign convention is to use the subscripts *in* and *out* to indicate direction.**

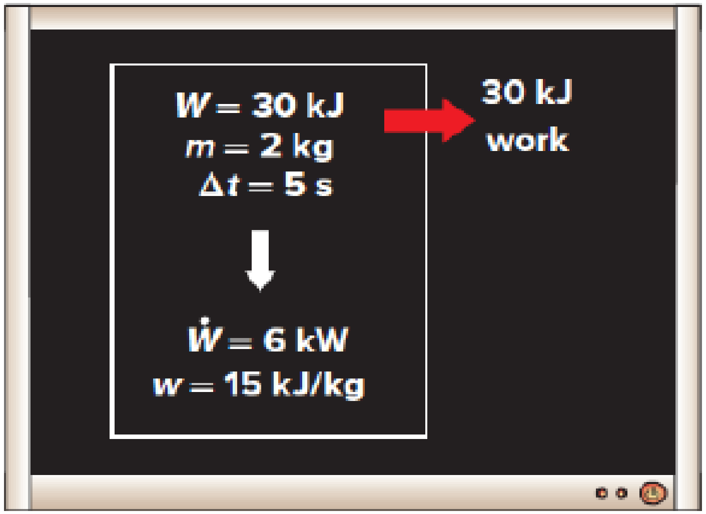


FIGURE 3-20
The relationships among w, W, and $\dot{W}$.

Work done per unit mass

$$w = \frac{W}{m} \quad \text{(kJ/kg)}$$

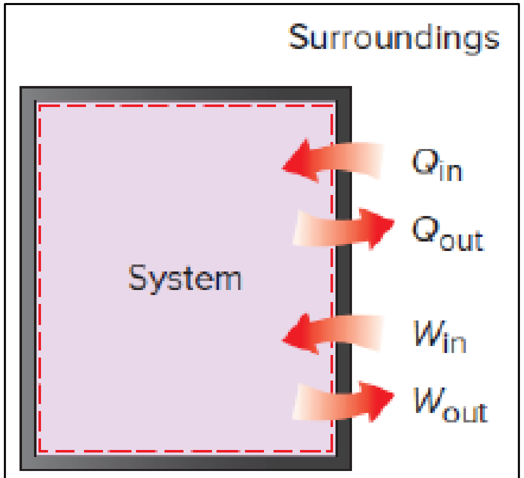


FIGURE 3-21
Specifying the directions of heat and work.

Heat vs. Work

- Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are ***boundary*** phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a ***process,*** not a state.
- Unlike properties, heat or work has no meaning at a state.
- Both are ***path functions*** (i.e., their magnitudes depend on the path followed during a process as well as the end states).

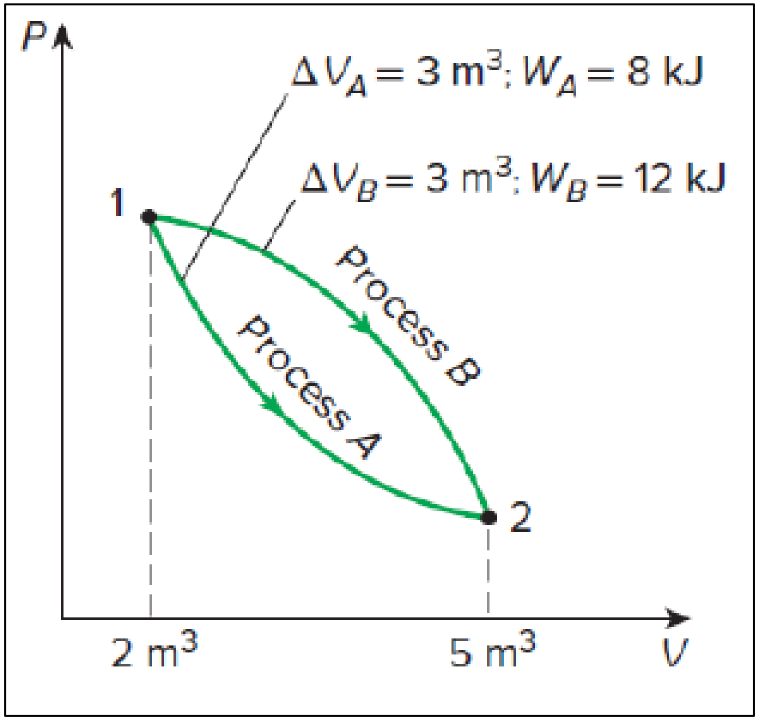


FIGURE 3-22
Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

Properties are point functions have exact differentials (d).

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

Path functions have inexact differentials (δ)

$$\int_1^2 \delta W = W_{12} \qquad (not\ \Delta W)$$

Electrical Work

When N coulombs of electrical charge move through a potential difference **V, the electrical work done is**

Electrical work

$$W_e = \mathbf{V} N$$

N=Coulomb of Electrical Charge

Electrical power

$$\dot{W}_e = \mathbf{V} I \qquad \text{(W)}$$

When potential difference and current change with time

$$W_e = \int_1^2 \mathbf{V} I \, dt \qquad \text{(kJ)}$$

When potential difference and current remain constant

$$W_e = \mathbf{V} I \Delta t \qquad \text{(kJ)}$$

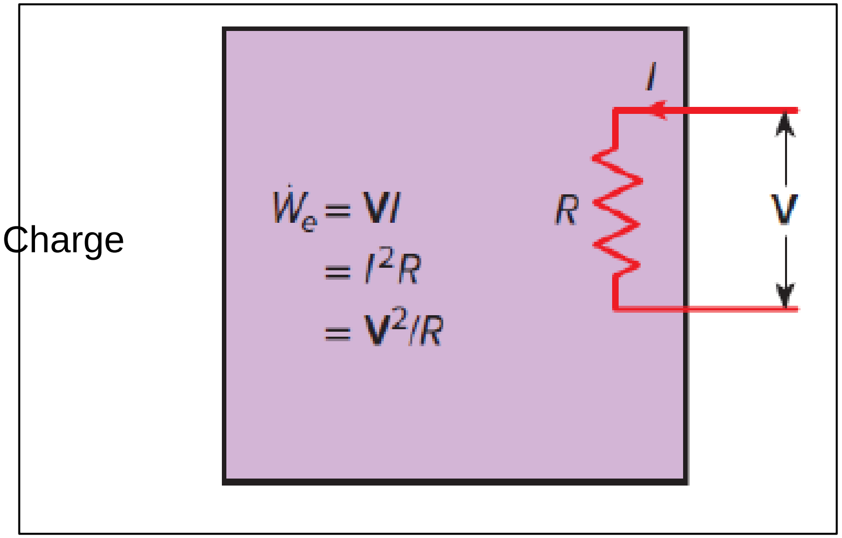


FIGURE 3-27
Electrical power in terms of resistance R, current I, and potential difference $\mathbf{V}$.

The **coulomb** is defined as the quantity of electricity transported in one second by a current of one ampere.

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EXAMPLE 3–2 **Wind Energy**

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s (Fig. 3–13). Determine the wind energy (*a*) per unit mass, (*b*) for a mass of 10 kg, and (*c*) for a flow rate of 1154 kg/s for air.

FIGURE 3–13
A site for a wind farm as discussed in Example 3–2.
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SOLUTION

A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

Assumptions

Wind flows steadily at the specified speed.

Analysis

The only harvestable form of energy of atmospheric air is the kinetic energy, which is captured by a wind turbine.

(a) Wind energy per unit mass of air is

$$e = \mathrm{ke} = \frac{V^2}{2} = \frac{(8.5\ \mathrm{m/s})^2}{2}\left(\frac{1\ \mathrm{J/kg}}{1\ \mathrm{m^2/s^2}}\right) = \mathbf{36.1\ J/kg}$$

(b) Wind energy for an air mass of 10 kg is

$$E = me = (10\ \mathrm{kg})(36.1\ \mathrm{J/kg}) = \mathbf{361\ J}$$

(c) Wind energy for a mass flow rate of 1154 kg/s is

$$\dot{E} = \dot{m}e = (1154\ \mathrm{kg/s})(36.1\ \mathrm{J/kg})\left(\frac{1\ \mathrm{kW}}{1000\ \mathrm{J/s}}\right) = \mathbf{41.7\ kW}$$

Discussion

It can be shown that the specified mass flow rate corresponds to a 12-m diameter flow section when the air density is 1.2 kg/m^3. Therefore, a wind turbine with a wind span diameter of 12 m has a power generation potential of 41.7 kW. Real wind turbines convert about one-third of this potential to electric power.

3-5 MECHANICAL FORMS OF WORK

- **There are two requirements for a work interaction between a system and its surroundings to exist:**
  - ✓ there must be a ***force*** acting on the boundary.
  - ✓ the boundary must ***move***.

Work = Force × Distance

$W = Fs$ (kJ)

When force is not constant

$$W = \int_1^2 F\,ds \qquad \text{(kJ)}$$

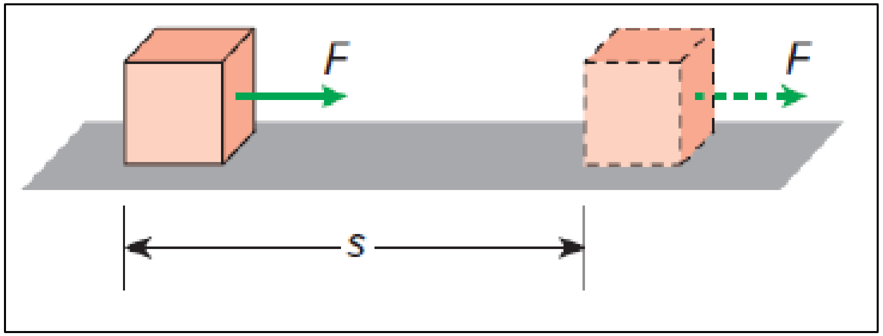


FIGURE 3-28
The work done is proportional to the force applied (*F*) and the distance traveled (*s*).

Shaft Work

A force *F* acting through a moment arm *r* generates a torque T

$$\mathrm{T} = Fr \rightarrow F = \frac{\mathrm{T}}{r}$$

This force acts through a distance *s*

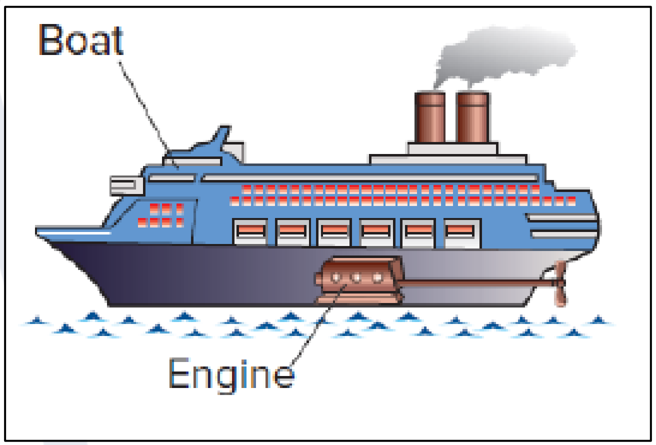
$$s = (2\pi r)n$$

Shaft work

$$W_{\mathrm{sh}} = Fs = \left(\frac{\mathrm{T}}{r}\right)(2\pi rn) = 2\pi n\mathbf{T} \qquad \text{(kJ)}$$

The power transmitted through the shaft is the shaft work done per unit time

$$\dot{W}_{\mathrm{sh}} = 2\pi\dot{n}\mathbf{T} \qquad \text{(kW)}$$



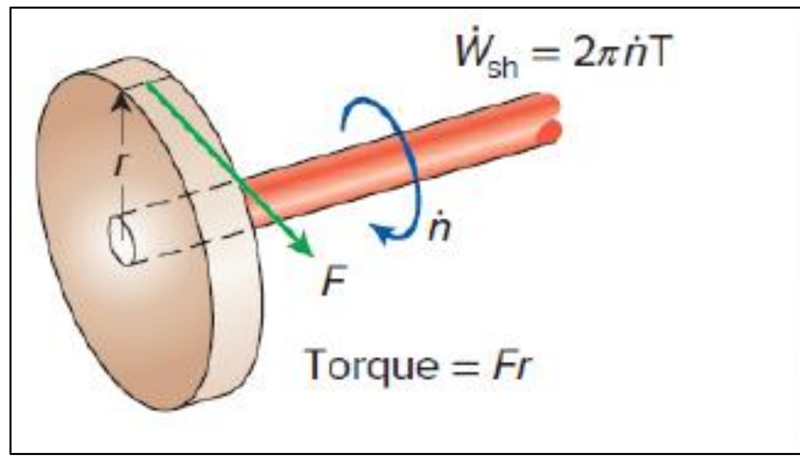
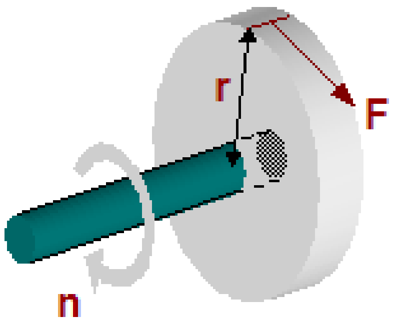


FIGURE 3-29
Energy transmission through rotating shafts is commonly encountered in practice.

FIGURE 3-30
Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

More details

Shaft Work :



The work associated with the transmission of energy through a rotating shaft is commonly encountered in many engineering problems.

$$\tau = F\,r \qquad \text{or:} \qquad F = \frac{\tau}{r}$$

This force acts through a distance (**s**), which is related to the number of revolutions by the perimeter, **2πr**, by the following equation:

$$s = (2\pi r)N$$

Where **N** is the number of revolutions that the **shaft** turns.

Recall that work is a force acting through a distance. Therefore:

$$W_s = F \cdot s = \frac{\tau}{r}(2\pi N r) = 2\pi\tau N$$

Accounting for the rate at which the shaft rotates, perhaps in **revolutions per minute** (**RPM**), we get the power transmitted through the shaft which is expressed below:

$$\dot{W}_s = 2\pi\tau\dot{N}$$

Spring Work

When the length of the spring changes by a differential amount *dx* under the influence of a force *F*, the work done is

$$\delta W_{\text{spring}} = F\,dx$$

For linear elastic springs, the displacement *x* is proportional to the force applied

$$F = kx \qquad \text{(kN)}$$

***k:*spring constant** (kN/m)

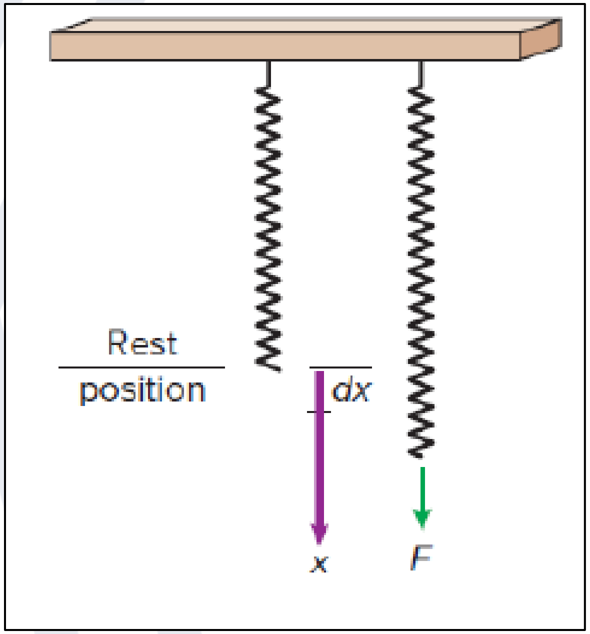


FIGURE 3-32
Elongation of spring under the influence of a force.

Substituting and integrating yield

$$W_{\text{spring}} = \frac{1}{2}k\left(x_2^2 - x_1^2\right) \qquad \text{(kJ)}$$

x_1 and x_2: the initial and the final displacements

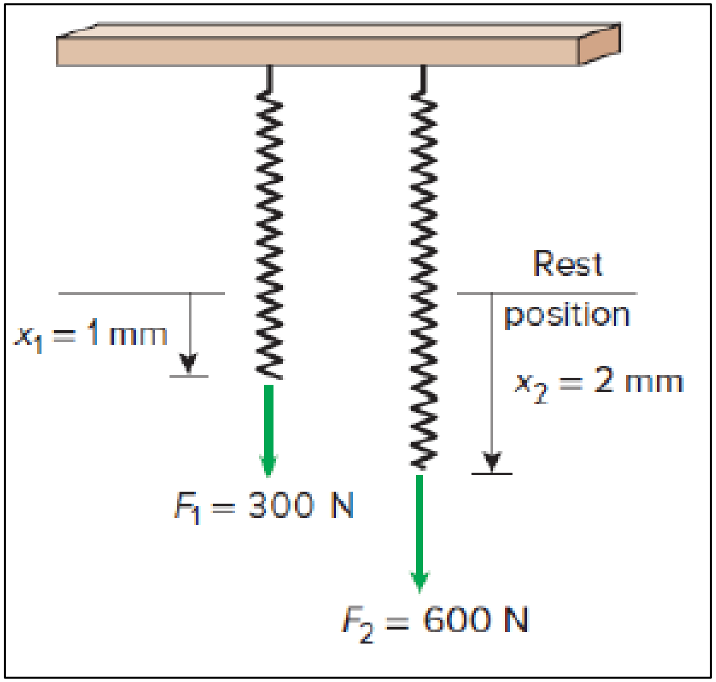


FIGURE 3-33
The displacement of a linear spring doubles when the force is doubled.

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EXAMPLE 3–7 Power Transmission by the Shaft of a Car

Determine the power transmitted through the shaft of a car when the torque applied is 200 N·m and the shaft rotates at a rate of 4000 revolutions per minute (rpm).

SOLUTION

The torque and the rpm for a car engine are given. The power transmitted is to be determined.

Analysis

A sketch of the car is given in **Fig. 3–31**. The shaft power is determined directly from

$$\dot{W}_{sh} = 2\pi\dot{n}T = (2\pi)\left(4000\,\frac{1}{\text{min}}\right)(200\ \text{N}\cdot\text{m})\left(\frac{1\ \text{min}}{60\ \text{s}}\right)\left(\frac{1\ \text{kJ}}{1000\ \text{N}\cdot\text{m}}\right)$$

$$= \mathbf{83.8\ kW} \quad (\text{or } 112\ \text{hp})$$

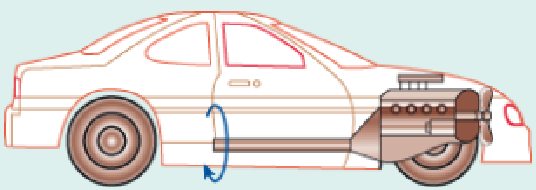

FIGURE 3–31
Schematic for **Example 3–7**.

Discussion

Note that power transmitted by a shaft is proportional to torque and the rotational speed.

EXAMPLE 3–8 Power Needs of a Car to Climb a Hill

Consider a 1200-kg car cruising steadily on a level road at 90 km/h. Now the car starts climbing a hill that is sloped 30° from the horizontal (**Fig. 3–37**). If the velocity of the car is to remain constant during climbing, determine the additional power that must be delivered by the engine.

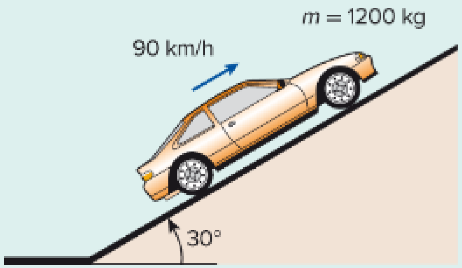

FIGURE 3–37
Schematic for **Example 3–8**.

SOLUTION

A car is to climb a hill while maintaining a constant velocity. The additional power needed is to be determined.

Analysis

The additional power required is simply the work that needs to be done per unit time to raise the elevation of the car, which is equal to the change in the potential energy of the car per unit time:

$$\dot{W}_g = mg\,\Delta z/\Delta t = mgV_{\text{vertical}}$$

$$= (1200\text{ kg})(9.81\text{ m/s}^2)(90\text{ km/h})(\sin 30°)\left(\frac{1\text{ m/s}}{3.6\text{ km/h}}\right)\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)$$

$$= 147\text{ kJ/s} = \mathbf{147\text{ kW}} \quad (\text{or } 197\text{ hp})$$

Discussion

Note that the car engine will have to produce almost 200 hp of additional power while climbing the hill if the car is to maintain its velocity.

Work Associated with the Stretching of a Liquid Film

σ_n= Normal Stress

σ_s= Surface Tension

$$W_{\text{surface}} = \int_1^2 \sigma_s \, dA \qquad (\text{kJ})$$

Work Done on Elastic Solid Bars

$$W_{\text{elastic}} = \int_1^2 F \, dx = \int_1^2 \sigma_n \, A \, dx \qquad (\text{kJ})$$

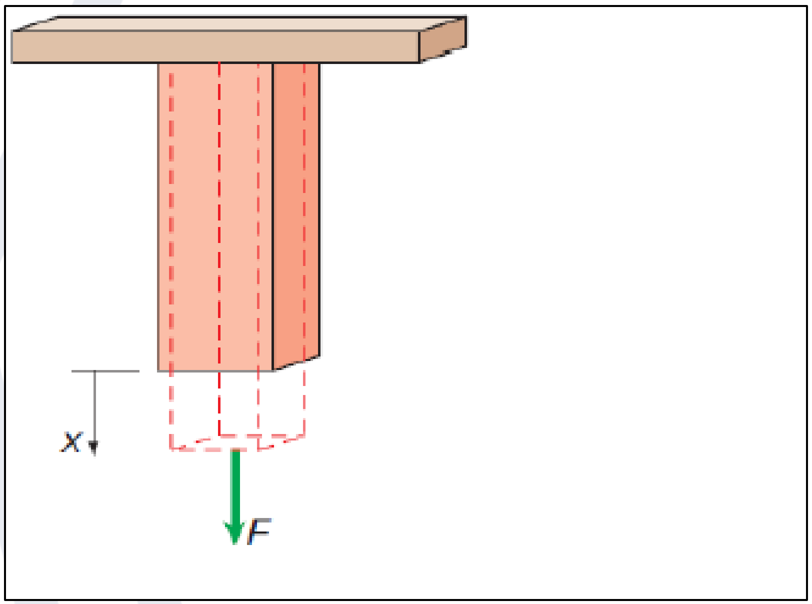

FIGURE 3-34
Solid bars behave as springs under the influence of a force.

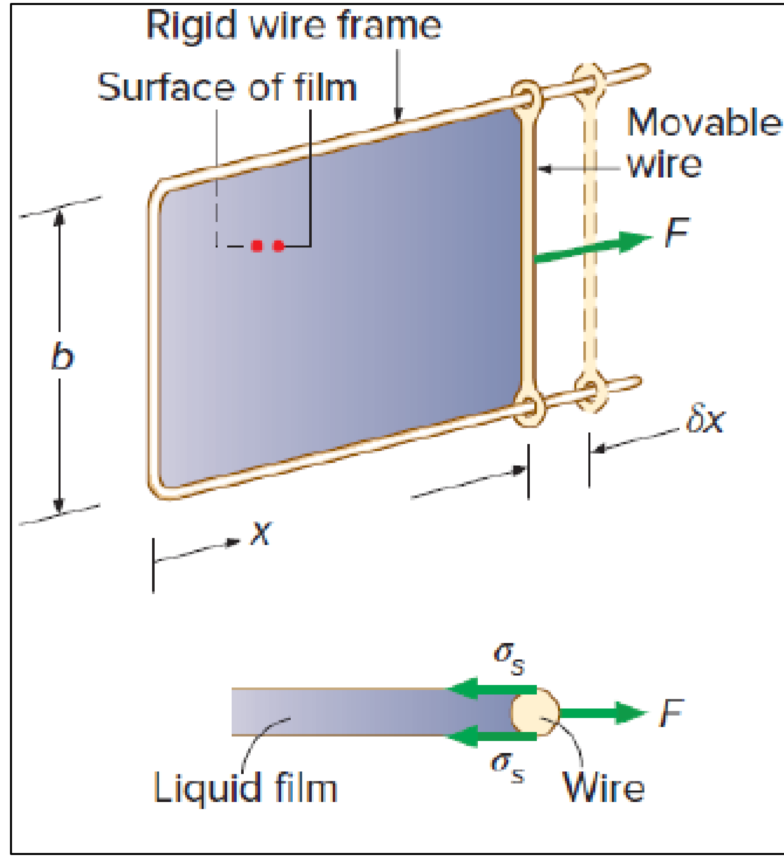

FIGURE 3-35
Stretching a liquid film with a U-shaped wire, and the forces acting on the movable wire of length *b*.

EXAMPLE 3–9 Power Needs of a Car to Accelerate

Determine the power required to accelerate a 900-kg car shown in Fig. 3–38 from rest to a velocity of 80 km/h in 20 s on a level road.

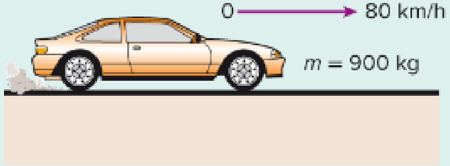

FIGURE 3–38
Schematic for Example 3–9.

SOLUTION

The power required to accelerate a car to a specified velocity is to be determined.

Analysis

The work needed to accelerate a body is simply the change in the kinetic energy of the body,

$$W_a = \tfrac{1}{2}m(V_2^2 - V_1^2) = \tfrac{1}{2}(900\text{ kg})\left[\left(\frac{80{,}000\text{ m}}{3600\text{ s}}\right)^2 - 0^2\right]\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)$$

$$= 222\text{ kJ}$$

The average power is determined from

$$\dot{W}_a = \frac{W_a}{\Delta t} = \frac{222\text{ kJ}}{20\text{ s}} = \mathbf{11.1\ kW} \quad (\text{or } 14.9\text{ hp})$$

Discussion

This is in addition to the power required to overcome friction, rolling resistance, and other imperfections.

Work Done to Raise or to Accelerate a Body

1. The work transfer needed to raise a body is equal to the change in the potential energy of the body.
2. The work transfer needed to accelerate a body is equal to the change in the kinetic energy of the body.

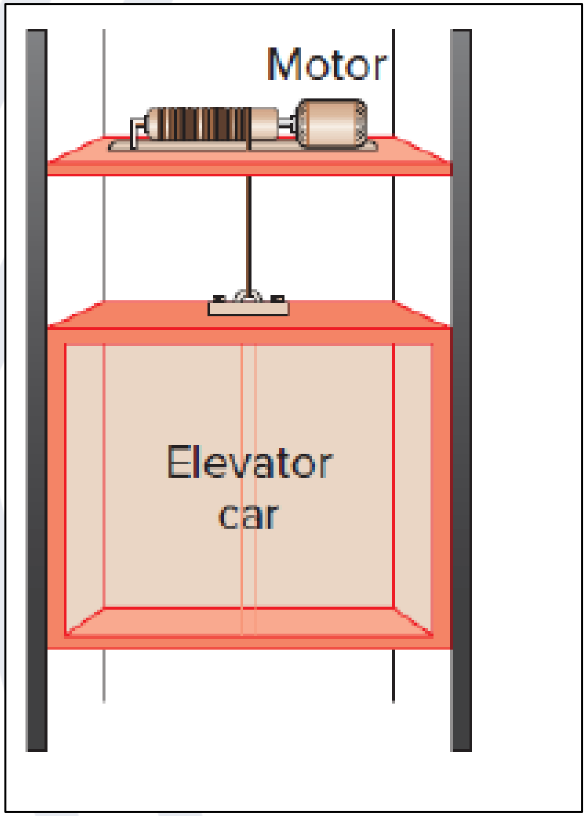

FIGURE 3-36
The energy transferred to a body while being raised is equal to the change in its potential energy.

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Nonmechanical Forms of Work

- **Electrical work:** **The generalized force is the *voltage* (the electrical potential) and the generalized displacement is the *electrical charge.***

- **Magnetic work:** **The generalized force is the *magnetic field strength* and the generalized displacement is the total *magnetic dipole moment.***

- **Electrical polarization work:** **The generalized force is the *electric field strength* and the generalized displacement is the *polarization of the medium.***

THE FIRST LAW OF THERMODYNAMICS

- **The *first law of thermodynamics* (*the conservation of energy principle*)** provides a sound basis for studying the relationships among the various forms of energy and energy interactions.

- The first law states that ***energy can be neither created nor destroyed during a process; it can only change forms***.

The *First Law:* For all adiabatic processes between two specified states of a <u>closed system</u>, the net work done is the same regardless of the nature of the closed system and the details of the process.

THE FIRST LAW OF THERMODYNAMICS

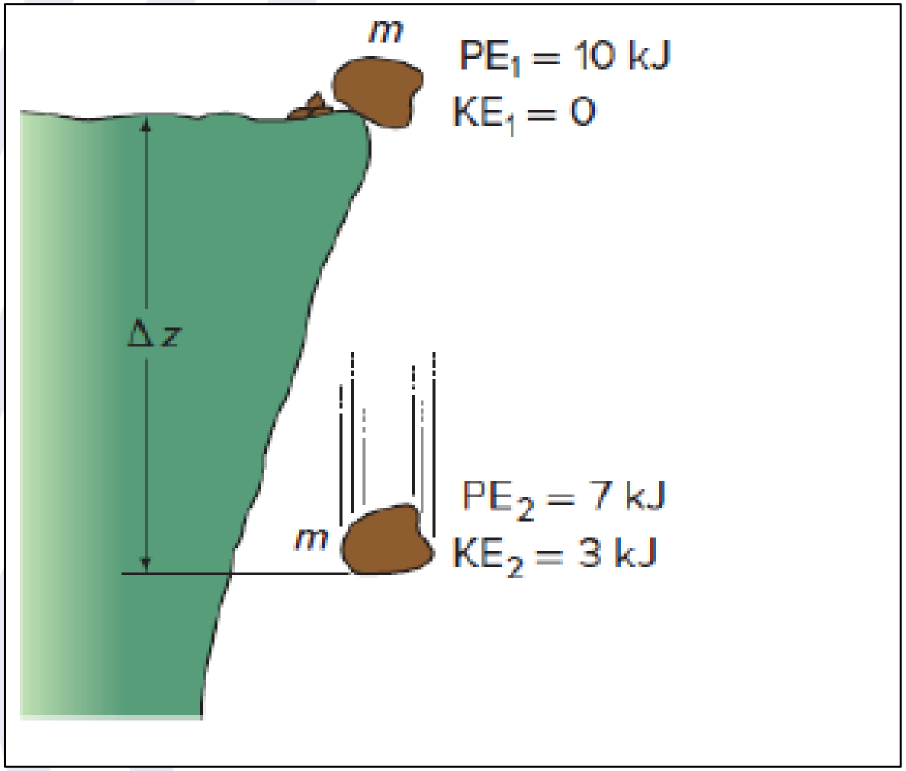


FIGURE 3-39
Energy cannot be created or destroyed; It can only change forms.

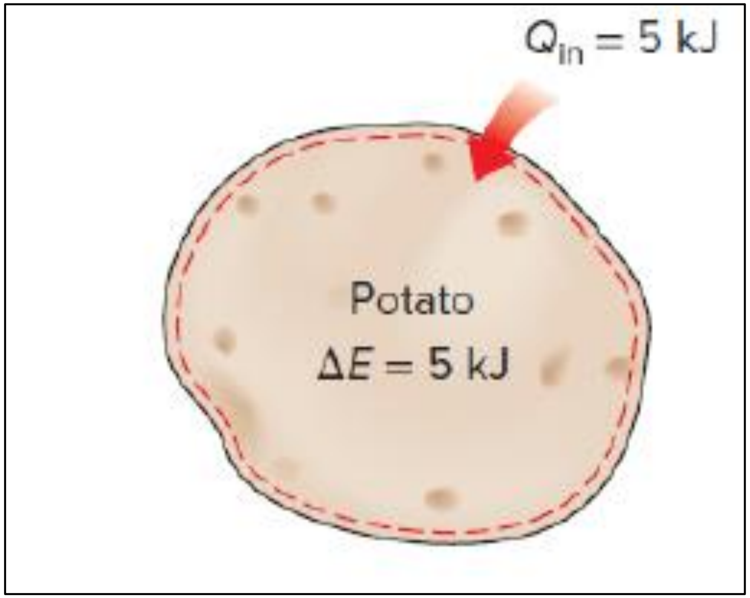
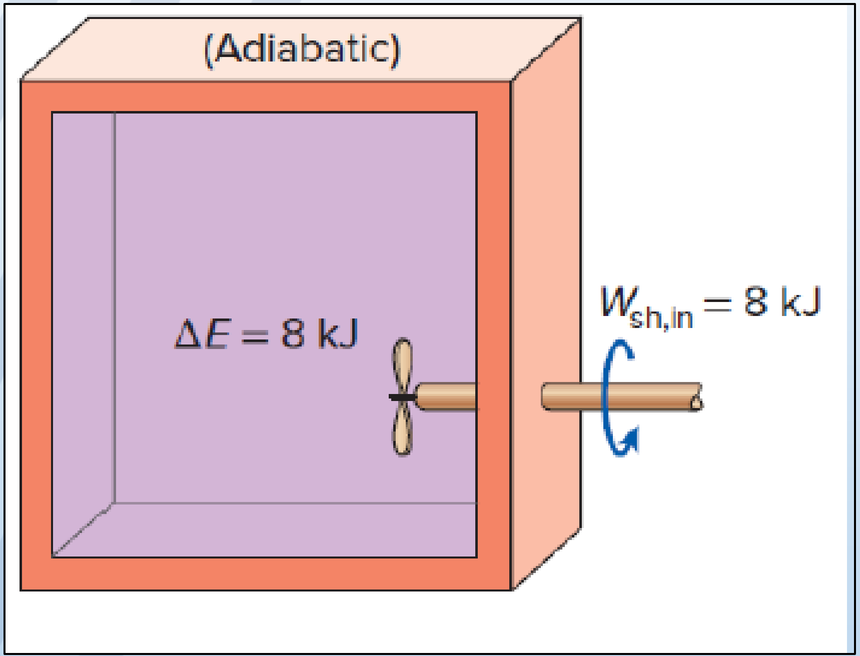


FIGURE 3-40
The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

THE FIRST LAW OF THERMODYNAMICS



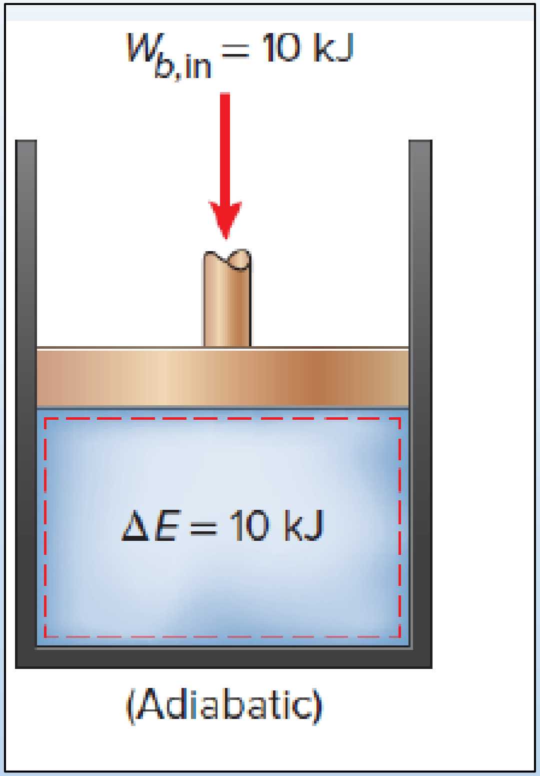
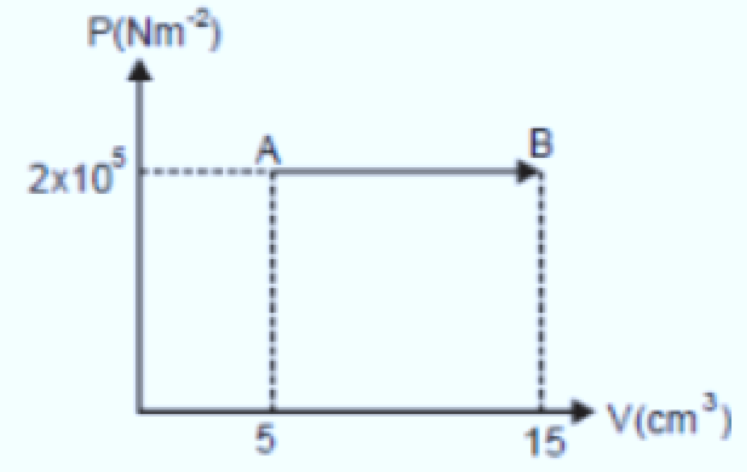


FIGURE 3-43
The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

FIGURE 3-44
The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

Example Problem no. 1: Based on the graph below, what is the work done by helium gas in the process AB?



Known :

Pressure (P) = 2×10^5 N/m^2 = 2×10^5 Pascal

Initial volume (V_1) = 5 cm^3 = 5×10^{-6} m^3

Final volume (V_2) = 15 cm^3 = 15×10^{-6} m^3

Calculate : Work done by gas in process AB

Solution :

The first law of thermodynamics

$W = \Delta P \, \Delta V$

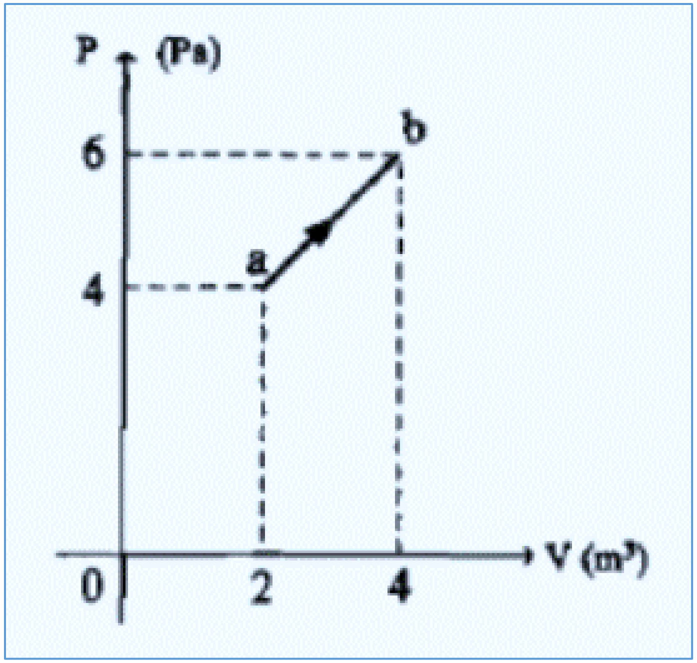
$W = P (V_2 - V_1)$

$W = (2 \times 10^5)(15 \times 10^{-6} - 5 \times 10^{-6})$

$W = (2 \times 10^5)(10 \times 10^{-6}) = (2 \times 10^5)(1 \times 10^{-5})$

$W = 2$ Joule

Example Problem 2: on the graph below, what is the work done in process a-b?



Known :

Initial pressure (P_1) = 4 Pa = 4 N/m^2

Final pressure (P_2) = 6 Pa = 6 N/m^2

Initial volume (V_1) = 2 m^3

Final volume (V_2) = 4 m^3

Calculate: work done I process a-b

Solution :

Work done by gas = area under curve a-b

W = area of triangle + area of rectangle

W = ½ (6-4)(4-2) + 4(4-2)

W = ½ (2)(2) + 4(2)

W = 2 + 8

W = 10 Joule

Energy Balance

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$$

The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.

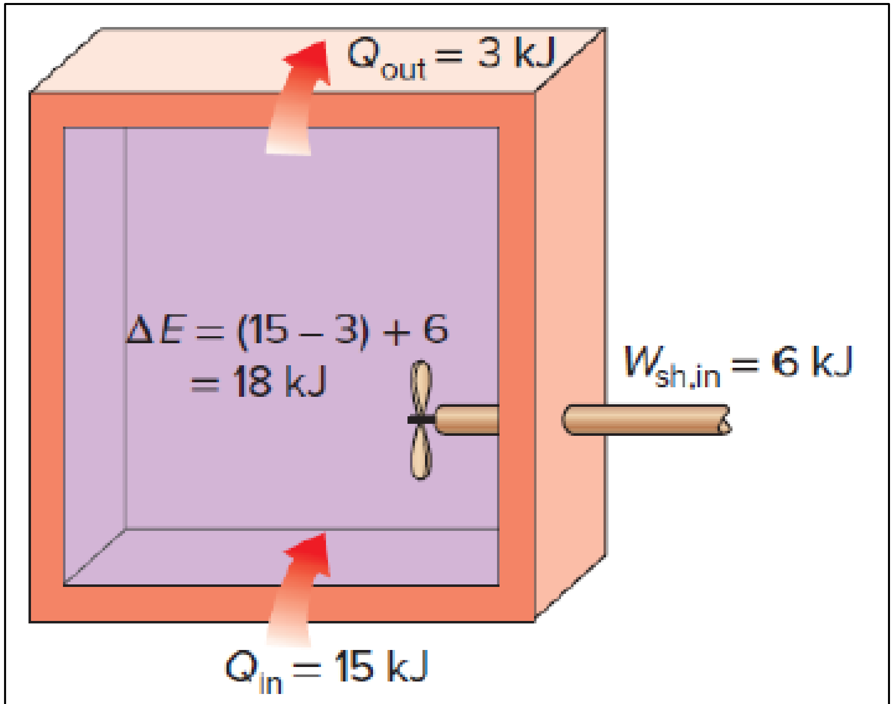


FIGURE 3-45
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

EXAMPLE 3–10 Cooling of a Hot Fluid in a Tank

A rigid tank contains a hot fluid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel.

SOLUTION

A fluid in a rigid tank looses heat while being stirred. The final internal energy of the fluid is to be determined.

Assumptions

1 The tank is stationary and thus the kinetic and potential energy changes are zero, ΔKE = ΔPE = 0. Therefore, $\Delta E = \Delta U$ and internal energy is the only form of the system's energy that may change during this process. **2** Energy stored in the paddle wheel is negligible.

Analysis

Take the contents of the tank as the system (Fig. 3–49). This is a *closed system* since no mass crosses the boundary during the process. We observe that the volume of a rigid tank is constant, and thus there is no moving boundary work. Also, heat is lost from the system and shaft work is done on the system. Applying the energy balance on the system gives

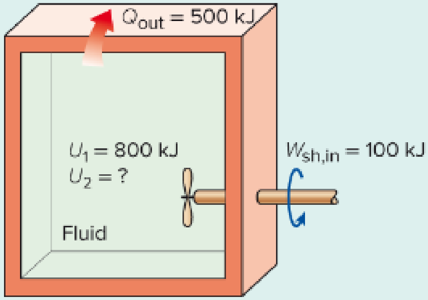


FIGURE 3–49

FIGURE 3–49
Schematic for **Example 3–10**.

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}}$$

$$W_{sh,\,in} - Q_{out} = \Delta U = U_2 - U_1$$

$$100 \text{ kJ} - 500 \text{ kJ} = U_2 - 800 \text{ kJ}$$

$$U_2 = \mathbf{400\ kJ}$$

Therefore, the final internal energy of the system is 400 kJ.

Energy Change of a System, ΔE_{system}

$$\text{Energy change} = \text{Energy at final state} - \text{Energy at initial state}$$

$$\Delta E_{\text{system}} = E_{\text{final}} - E_{\text{initial}} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta \text{KE} + \Delta \text{PE}$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

$$\Delta \text{KE} = \frac{1}{2} m\left(V_2^2 - V_1^2\right)$$

$$\Delta \text{PE} = mg(z_2 - z_1)$$

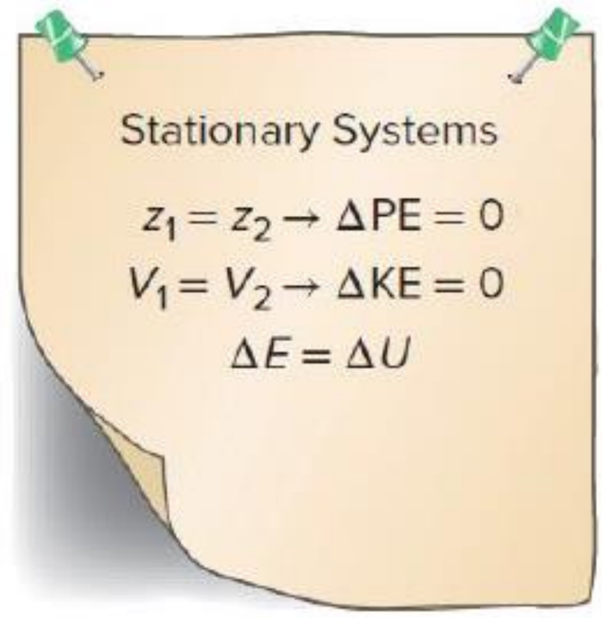


FIGURE 3-46
For stationary systems,
$\Delta \text{KE} = \Delta \text{PE} = 0$; thus $\Delta E = \Delta U$.

Mechanisms of Energy Transfer, E_{in} and E_{out}

Energy balance for any system undergoing any kind of process can be expressed more compactly as

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}} \quad (\text{kJ}) \qquad \textbf{(3-35)}$$

or, in the rate form, as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}} / dt}_{\substack{\text{Rate of change in internal,} \\ \text{kinetic, potential, etc., energies}}} \quad (\text{kW}) \qquad \textbf{(3-36)}$$

Mechanisms of Energy Transfer, E_{in} and E_{out}

For constant rates, the total quantities during a time interval $\triangle t$ are related to the quantities per unit time as

$$Q = \dot{Q} \triangle t, W = \dot{W} \triangle t, \text{and } \triangle E = (dE/dt) \triangle t \quad (\text{kJ}) \qquad \textbf{(3-37)}$$

The energy balance can be expressed on a per unit mass basis as

$$e_{in} - e_{out} = \triangle e_{system} \ (\text{kJ/kg}) \qquad \textbf{(3-38)}$$

which is obtained by dividing all the quantities in Eq.3-35 by the mass m of the system. Energy balance can also be expressed in the differential form as

$$\delta E_{in} - \delta E_{out} = dE_{system} \ \textbf{or} \ \delta e_{in} - \delta e_{out} = de_{system} \qquad \textbf{(3-39)}$$

Mechanisms of Energy Transfer, E_{in} and E_{out}

Mechanisms of energy transfer:

- **Heat transfer**
- **Work transfer**
- **Mass flow**

A closed mass involves only heat transfer and work.

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + \left(E_{mass,in} - E_{mass,out}\right) = \Delta E_{system}$$

$W_{net,out} = Q_{net,in}$ or $\dot{W}_{net,out} - \dot{Q}_{net,in}$ (for a cycle)

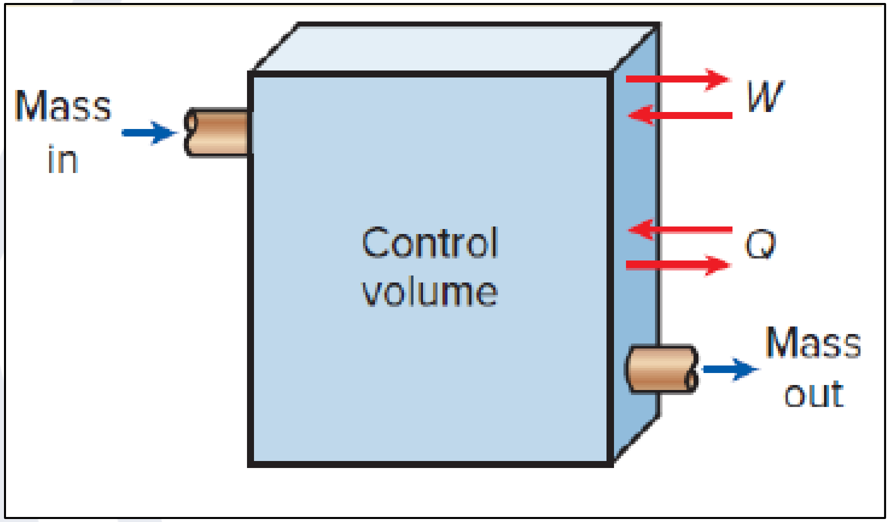


FIGURE 3-47
The energy content of a control volume can be changed by mass flow as well as heat and work interactions.

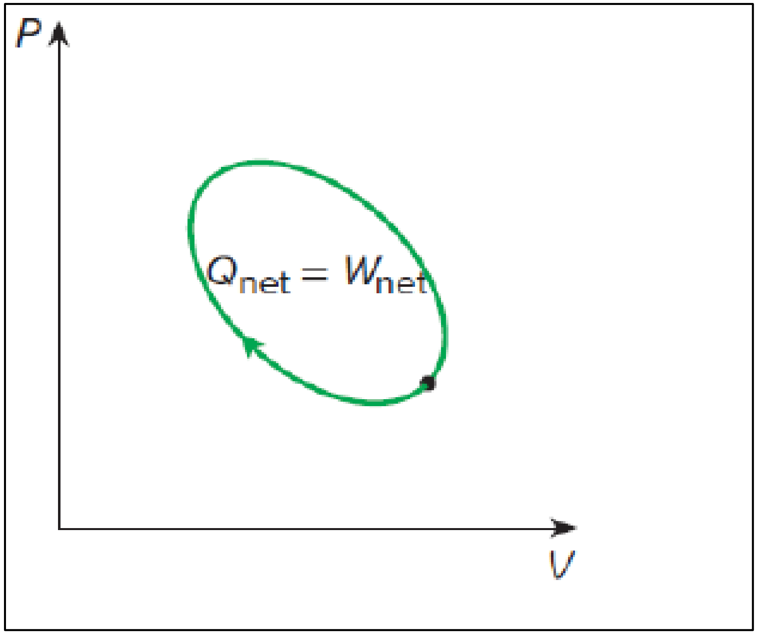


FIGURE 3-48
For a cycle $\Delta E = 0$, thus $Q = W$.

3-7 ENERGY CONVERSION EFFICIENCIES

Efficiency is one of the most frequently used terms in thermodynamics, and it indicates how well an energy conversion or transfer process is accomplished.

$$\text{Efficiency} = \frac{\text{Desired output}}{\text{Required output}}$$

Efficiency of a water heater: **The ratio of the energy delivered to the house by hot water to the energy supplied to the water heater.**

Type	Efficiency
Gas, conventional	55%
Gas, high-efficiency	62%
Electric, conventional	90%
Electric, high-efficiency	94%

FIGURE 3-53

Typical efficiencies of conventional and high-efficiency electric and natural gas water heaters.

Water heater

ENERGY CONVERSION EFFICIENCIES

$$\eta_{combustion} = \frac{Q}{HV} = \frac{\text{Amount of heat released during } \textit{combustion}}{\text{Heating value of the fuel } \textit{burned}}$$

Heating value of the fuel: The amount of heat released when a unit amount of fuel at room temperature is completely burned and the combustion products are cooled to the room temperature.

Lower heating value (LHV): When the water leaves as a vapor.

Higher heating value (HHV): When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.

Energy Conversion Efficiencies

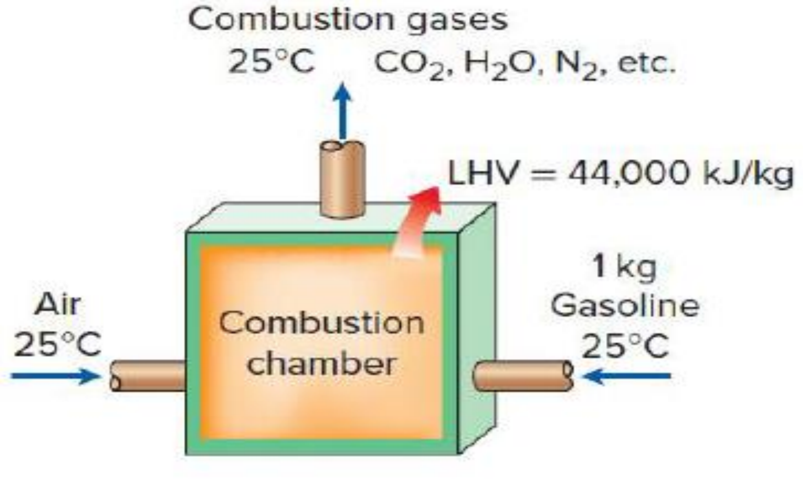


FIGURE 3-54
The definition of the heating value of gasoline.

- **The efficiency of space heating systems of residential and commercial buildings is usually expressed in terms of the annual fuel utilization efficiency (AFUE),**
- **which accounts for the combustion efficiency as well as other losses such as heat losses to unheated areas and start-up and cooldown losses.**

Example Problem

A cubic meter of water at room temperature has a weight of 9800 N at a location where g = 9.80 m/s2. What is its specific weight and its density at a location where g = 9.77 m/s2?

The mass of the water is

$$m = \frac{W}{g} = \frac{9800}{9.8} = 1000\ \text{kg}$$

Its weight where $g = 9.77\ \text{m/s}^2$ is $W = mg = (1000)(9.77) = 9770\ \text{N}$.

Specific weight: $$\gamma = \frac{W}{V} = \frac{9770}{1} = 9770\ \text{N/m}^3$$

Density: $$\rho = \frac{m}{V} = \frac{1000}{1} = 1000\ \text{kg/m}^3$$

ENERGY CONVERSION EFFICIENCIES

Overall efficiency of a power plant

$$\eta_{\text{overall}} = \eta_{\text{combustion}}\,\eta_{\text{thermal}}\,\eta_{\text{generator}} = \frac{\dot{W}_{\text{net,electric}}}{\text{HHV} \times \dot{m}_{\text{fuel}}}$$

- **Generator: A device that converts mechanical energy to electrical energy.**
- **Generator efficiency: The ratio of the electrical power output to the mechanical power input.**
- **Thermal efficiency of a power plant: The ratio of the net electrical power output to the rate of fuel energy input.**

3-7 ENERGY CONVERSION EFFICIENCIES-3

TABLE 2-1

The efficacy of different lighting systems

Type of lighting	Efficacy, lumens/W
Combustion	
Candle	0.3
Kerosene lamp	1-2
Incandescent	
Ordinary	6-20
Halogen	15-35
Fluorescent	
Compact	40-87
Tube	60-120
High-intensity discharge	
Mercury vapor	40-60
Metal halide	65-118
High-pressure sodium	85-140
Low-pressure sodium	70-200
Solid-State	
LED	20-160
OLED	15-60
Theoretical limit	300*

Lighting efficacy: The amount of light output in lumens per W of electricity consumed.

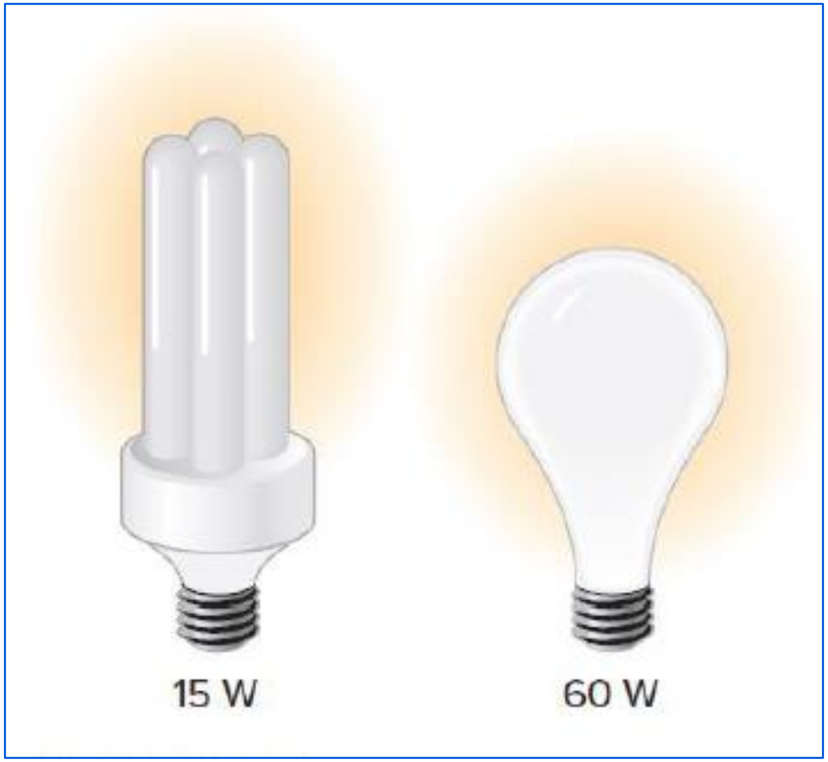
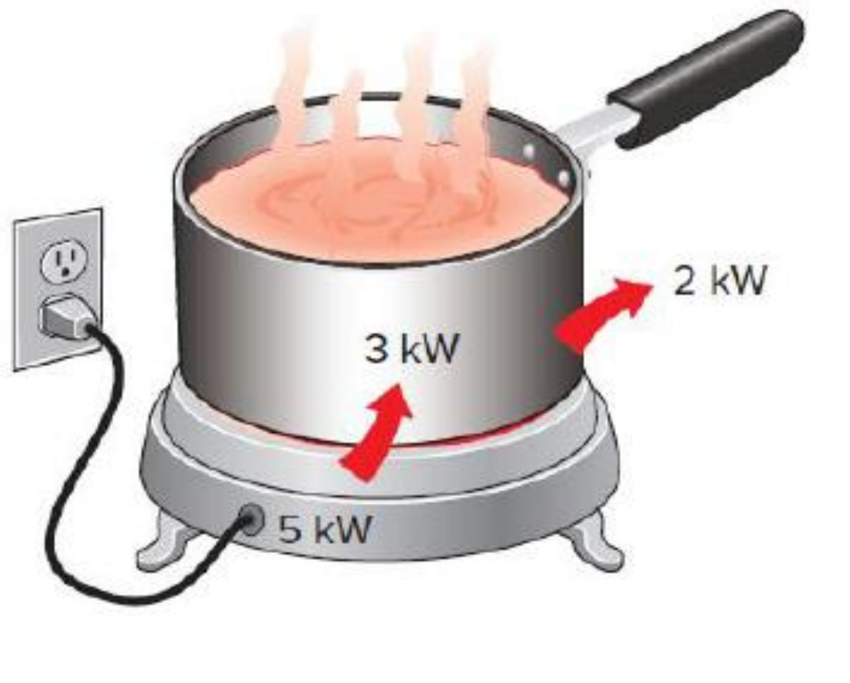


FIGURE 3-55
A 15-W compact fluorescent lamp provides as much light as a 60-W incandescent lamp.

3-7 ENERGY CONVERSION EFFICIENCIES-4

- Using energy-efficient appliances conserve energy.
- It helps the environment by reducing the amount of pollutants emitted to the atmosphere during the combustion of fuel.
- The combustion of fuel produces:
  - carbon dioxide, causes global warming
  - nitrogen oxides and hydrocarbons, cause smog
  - carbon monoxide, toxic
  - sulfur dioxide, causes acid rain.



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}} = \frac{3\text{kWh}}{5\text{kwh}} = 0.60$$

FIGURE 3-56

The efficiency of a cooking appliance represents the fraction of the energy supplied to the appliance that is transferred to the food.

3-7 ENERGY CONVERSION EFFICIENCIES-5

TABLE 3-2

Energy costs of cooking a casserole with different appliances*

[From J.T. Amann, A.Wilson, and K. Ackerly, *Consumer Guide to Home Energy Savings*, 9th ed., American Council for an Energy-Efficient Economy, Washington, D.C., 2007, p. 163.]

Cooking appliance	Cooking Temperature	Cooking Time	Energy Used	Cost of energy
Electric oven	350°F (177°C)	1 h	2.0 kWh	$0.19
Convection oven (elect.)	325°F (163°C)	45 min	1.39 kWh	$0.13
Gas oven	350°F (177°C)	1 h	0.112 therm	$0.13
Frying pan	420°F (216°C)	1 h	0.9 kWh	$0.09
Toaster Oven	425°F (218°C)	50 min	0.95 kWh	$0.09
Crockpot	200°F (93°C)	7 h	0.7 kWh	$0.07
Microwave oven	"High"	15 min	0.36 kWh	$0.03

***Assumes a unit cost of $0.095/kWh for electricity and $1.20/therm for gas.**

Efficiencies of Mechanical and Electrical Devices

Mechanical efficiency

$$\eta_{mech} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{mech,out}}{E_{mech,in}} = 1 - \frac{E_{mech,loss}}{E_{mech,in}}$$

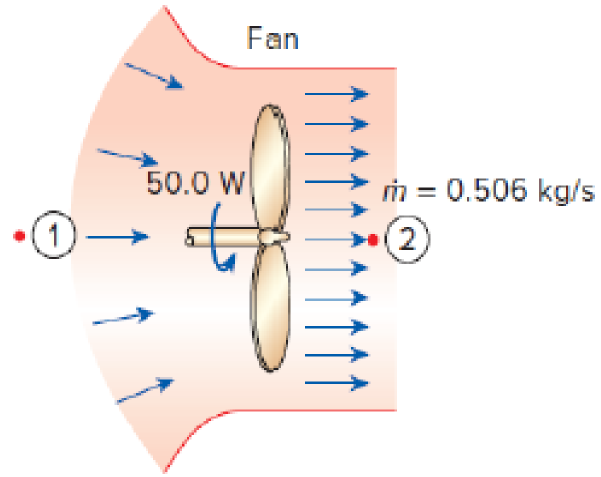
The effectiveness of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by the pump efficiency and turbine efficiency,

$$\eta_{pump} = \frac{\text{Mechanical energy increse of the fluid}}{\text{Mechanical energy input}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{W}_{pump,u}}{\dot{W}_{pump}}$$

$$\triangle \dot{E}_{mech,fluid} = \dot{E}_{mech,out} - \dot{E}_{mech,in}$$

$$\eta_{turbine} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decrease of the fluid}} = \frac{\dot{W}_{shaft,out}}{|\Delta \dot{E}_{mech,fluid}|} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine.e}}$$

$$|\Delta \dot{E}_{mech,fluid}| = \dot{E}_{mech,in} - \dot{E}_{mech,out}$$



$V_1 \approx 0$, $V_2 = 12.1$ m/s
$z_1 = z_2$
$P_1 \approx P_{atm}$ and $P_2 \approx P_{atm}$

$$\eta_{mech,\,fan} = \frac{\Delta \dot{E}_{mech,\,fluid}}{\dot{W}_{shaft,\,in}} = \frac{\dot{m}V_2^2/2}{\dot{W}_{shaft,\,in}} = \frac{(0.506\text{ kg/s})(12.1\text{ m/s})^2/2}{50.0\text{ W}} = 0.741$$

FIGURE 3-58
The mechanical efficiency of a fan is the ratio of the rate of increase of the mechanical energy of air to the mechanical power input.

Efficiencies of Mechanical and Electrical Devices-1

$$\eta_{\text{motor}} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{\text{shaft,out}}}{\dot{W}_{\text{elect,in}}}$$

Pump efficiency

$$\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{shaft,in}}}$$

Generator efficiency

$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{elect,in}}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{elect,in}}}$$

Pump-Motor overall efficiency

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{turbine},e}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|}$$

Turbine-Generator overall efficiency

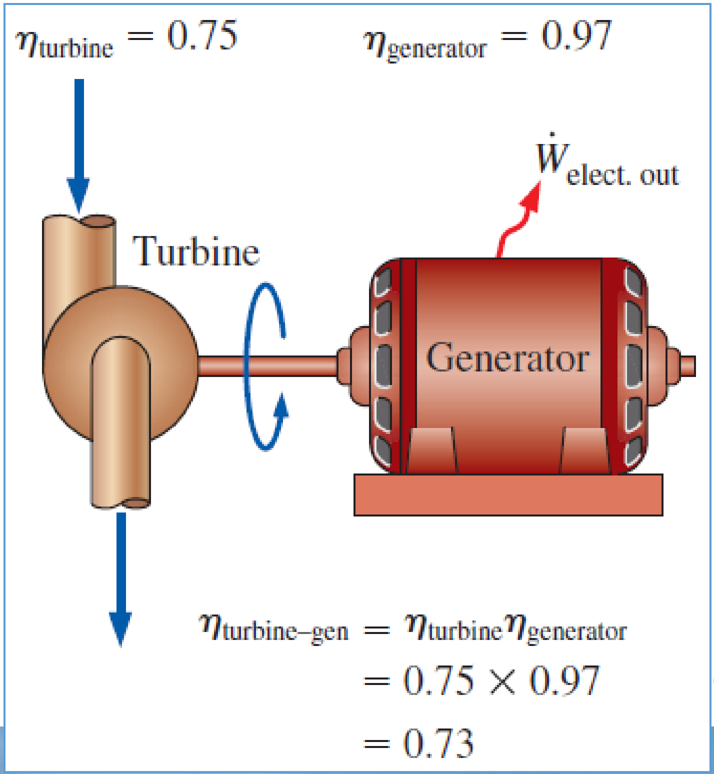


FIGURE 3-59
The overall efficiency of a turbine- generator is the product of the efficiency of the turbine and the efficiency of the generator, and represents the fraction of the mechanical power of the fluid converted to electrical power.

Summary

- **Forms of energy**

  Macroscopic = kinetic + potential

  Microscopic = Internal energy (sensible + latent + chemical + nuclear)
- **Energy transfer by heat**
- **Energy transfer by work**
- **Mechanical forms of work**
- **The first law of thermodynamics**

  Energy balance

  Energy change of a system

  Mechanisms of energy transfer (heat, work, mass flow)
- **Energy conversion efficiencies**

  Efficiencies of mechanical and electrical devices (turbines, pumps).

SUMMARY

The sum of all forms of energy of a system is called *total energy,* which consists of internal, kinetic, and potential energy for simple compressible systems. *Internal energy* represents the molecular energy of a system and may exist in sensible, latent, chemical, and nuclear forms.

Mass flow rate $\dot{m}$ is defined as the amount of mass flowing through a cross section per unit time. It is related to the *volume flow rate* $\dot{V}$, which is the volume of a fluid flowing through a cross section per unit time, by

$$\dot{m} = \rho\dot{V} = \rho A_c V_{\text{avg}}$$

The energy flow rate associated with a fluid flowing at a rate of $\dot{m}$ is

$$\dot{E} = \dot{m}e$$

which is analogous to $E = me$.

The *mechanical energy* is defined as *the form of energy that can be converted to mechanical work completely and directly by a mechanical device such as an ideal turbine*. It is expressed on a unit mass basis and rate form as

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

and

$$\dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

where P/ρ is the *flow energy*, $V^2/2$ is the *kinetic energy*, and gz is the *potential energy* of the fluid per unit mass.

Energy can cross the boundaries of a closed system in the form of heat or work. For control volumes, energy can also be transported by mass. If the energy transfer is due to a temperature difference between a closed system and its surroundings, it is *heat;* otherwise, it is *work.*

Work is the energy transferred as a force acts on a system through a distance. Various forms of work are expressed as follows:

Work is the energy transferred as a force acts on a system through a distance. Various forms of work are expressed as follows:

Electrical work: $W_e = VI\,\Delta t$

Shaft work: $W_{sh} = 2\pi n T$

Spring work:

$$W_{spring} = \frac{1}{2}k(x_2^2 - x_1^2)$$

The *first law of thermodynamics* is essentially an expression of the conservation of energy principle, also called the *energy balance*. The general energy balance for *any system* undergoing *any process* can be expressed as

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}} \qquad \text{(kJ)}$$

It can also be expressed in the *rate form* as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal,} \\ \text{kinetic, potential, etc., energies}}} \qquad \text{(kW)}$$

The efficiencies of various devices are defined as

$$\eta_{pump} = \frac{\Delta \dot{E}_{mech,\ fluid}}{\dot{W}_{shaft,\ in}} = \frac{\dot{W}_{pump,\ u}}{\dot{W}_{pump}}$$

$$\eta_{turbine} = \frac{\dot{W}_{shaft,\ out}}{|\Delta \dot{E}_{mech,\ fluid}|} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine,\ e}}$$

$$\eta_{motor} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{shaft,\ out}}{\dot{W}_{elect,\ in}}$$

$$\eta_{generator} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{elect,\ out}}{\dot{W}_{shaft,\ in}}$$

$$\eta_{pump-motor} = \eta_{pump}\eta_{motor} = \frac{\Delta \dot{E}_{mech,\ fluid}}{\dot{W}_{elect,\ in}}$$

$$\eta_{turbine-gen} = \eta_{turbine}\eta_{generator} = \frac{\dot{W}_{elect,\ out}}{|\Delta \dot{E}_{mech,\ fluid}|}$$

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EXAMPLE 1.10 A 2200-kg automobile traveling at 90 kph (25 m/s) hits the rear of a stationary, 1000-kg automobile. After the collision the large automobile slows to 50 kph (13.89 m/s), and the smaller vehicle has a speed of 88 kph (24.44 m/s). What has been the increase in internal energy, taking both vehicles as the system? The kinetic energy before the collision is (V = 25 m/s)

$$KE_1 = \frac{1}{2}m_a V_{a1}^2 = \left(\frac{1}{2}\right)(2200)(25^2) = 687\,500\text{ J}$$

After the collision the kinetic energy is

$$KE_2 = \frac{1}{2}m_a V_{a2}^2 + \frac{1}{2}m_b V_{b2}^2 = \left(\frac{1}{2}\right)(2200)(13.89^2) + \left(\frac{1}{2}\right)(1000)(24.44^2) = 510\,900\text{ J}$$

The conservation of energy requires that

$$E_1 = E_2 \qquad KE_1 + U_1 = KE_2 + U_2$$

Thus, $U_2 - U_1 = KE_1 - KE_2 = 687\,500 - 510\,900 = 176\,600$ J or 176.6 kJ.

Example: A 10-kg body falls from rest, with negligible interaction with its surroundings (no friction). Determine its velocity after it falls 5 m.

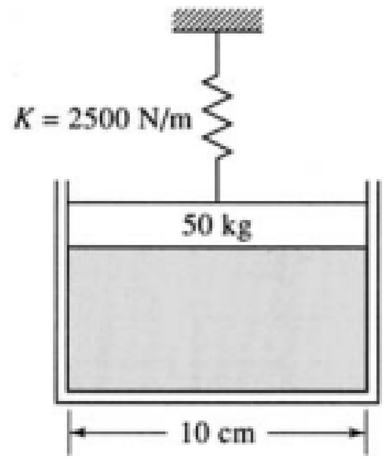
Conservation of energy demands that the initial energy of the system equal the final energy of the system; that is,

$$E_1 = E_2 \qquad \frac{1}{2}mV_1^2 + mgh_1 = \frac{1}{2}mV_2^2 + mgh_2$$

The initial velocity V_1 is zero, and the elevation difference $h_1 - h_2 = 5$ m. Thus, we have

$$mg(h_1 - h_2) = \frac{1}{2}mV_2^2 \qquad \text{or} \qquad V_2 = \sqrt{2g(h_1 - h_2)} = \sqrt{(2)(9.81)(5)} = 9.90 \text{ m/s}$$

EXAMPLE : The air in a circular cylinder (Fig. 3-10) is heated until the spring is compressed 50 mm. Find the work done by the air on the frictionless piston. The spring is initially unstretched, as shown.



The pressure in the cylinder is initially found from a force balance:

$$P_1 A_1 = P_{atm} A + W \qquad P_1 \frac{\pi(0.1)^2}{4} = (100\,000)\frac{\pi(0.1)^2}{4} + (50)(9.81)$$

$$\therefore P_1 = 162\,500 \text{ Pa}$$

To raise the piston a distance of 50 mm, without the spring, the pressure would be constant and the work required would be force times distance:

$$W = PA \times d = (162\,500)\frac{\pi(0.1)^2}{4}(0.05) = 63.81 \text{ J}$$

Using (*3.12*), the work required to compress the spring is calculated to be

$$W = \tfrac{1}{2}K(x_2^2 - x_1^2) = (\tfrac{1}{2})(2500)(0.05^2) = 3.125 \text{ J}$$

The total work is then found by summing the above two values: $W_{total} = 63.81 + 3.125 = 66.94$ J.